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An Evaluation of the Severity of the January 1998 Ice Storm in Northern New England

Report for FEMA Region 1

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EXECUTIVE SUMMARY

A severe freezing-rain storm hit Canada and the northeastern United States the week of January 5, 1998. Warm moist air from the Gulf of Mexico encountered cold Arctic air in three Canadian provinces and in northern New York, Vermont, New Hampshire, and Maine. This set up the classic scenario for freezing rain, as the less dense, warm Gulf air was forced up over the layer of Arctic air. The liquid precipitation cooled as it fell through the cold air and then froze on trees and structures when the latent heat of fusion was removed, primarily by convective and evaporative cooling. Ice accreting on trees and overhead lines caused hundreds of millions of dollars of damage in both the United States and Canada and left hundreds of thousands of people without power for periods ranging from a few hours to more than three weeks. In the United States the President declared disasters in five New York counties, six Vermont counties, and all New Hampshire and Maine counties except along the coast.

Over generally flat terrain within the storm footprint, such as the St. Lawrence and Champlain valleys, ice loading was severe and fairly uniform. In the mountainous terrain in Vermont and New Hampshire, ice loads varied with elevation and exposure. Valleys often remained warm enough that little or no ice formed. Trees and structures at elevations above about 4000 ft in the warm air layer also were unaffected. Below 4000 ft severe ice loads generally extended to lower elevations on the east-facing sides of mountains than on the west-facing sides. The very large ice loads reported on some towers on mountaintops are consistent with the accretion of ice from supercooled clouds in the layer of cold air, in addition to the ice from freezing rain.

The January ice storm was the worst ever in the experience of many people in upstate New York and northern New England, both in the amount of ice that accreted on trees and structures, and the extent of the storm. Both of these factors, along with the rural character of the region, contributed to the long power outages. Power outages caused by tree damage to the electrical distribution system tend to be long-lasting because a) damaged trees must first be removed to gain access to the downed line and b) all portions of a circuit must be repaired before any customers on that circuit can be brought back on line. In rural areas where miles of distribution line may serve only a few customers, outages may be prolonged. Fortunately, wind speeds associated with this storm were generally moderate throughout the region. If winds had increased after the ice storm, but before the accreted ice melted, as sometimes happens, there would have been much more damage.

The January storm is not without precedent. Sixty-eight years ago, in December of 1929, an ice storm that extended from western New York into Maine caused tree and overhead line damage comparable to that in this storm. This is consistent with return periods estimated by our extreme value analysis of between 35 and 85 years for severe ice storms in the Northeast with uniform ice thicknesses between 0.75 and 1.25 in. Other storms since 1929 have generated ice loads comparable to these, but over a smaller region.

For the most part, structures that were designed for heavy ice withstood the loads imposed by this storm. There was little damage to high-voltage transmission lines and communication towers in northern New England. However, lower-voltage transmission lines in narrow right-of-ways, distribution lines, and service drops vulnerable to damage from broken branches and trees took a beating. As has long been recognized, the level of damage to these structures from ice-loaded trees could be reduced by expert and frequent tree trimming and the removal of danger trees adjacent to the right-of-ways.

Severe ice storms are not confined to this part of the country. A widespread ice storm in the Southeast in February 1994 caused month-long power outages in Mississippi and brought down more than 16 communication towers. Back-to-back storms in Iowa in 1990 and 1991, the second followed by cold temperatures and high winds, caused cascade failures of hundreds of miles of transmission lines. Although some utilities design their major transmission lines for a heavy ice load, they are required to design only for the loads specified by the National Electrical Safety Code. The completion of the ice load and concurrent wind speed map proposed for ASCE 7-98 would provide 50-year return-period loads from freezing rain over the entire country for use in the design of ice-sensitive structures.

When ice-sensitive structures, including communication towers and power transmission lines, fail in an ice storm, it is often assumed that the ice load on the structure was greater than the load it was designed for. The obvious simplistic solution is then to design for a larger ice load. However, the collapse may have been initiated by a single component failing, perhaps because of previous damage or deterioration. When that component fails, the transfer of the load it was carrying, including the ice load and the wind load on the ice-covered structure, may overload other parts of the structure, which then may fail under a load they were not designed for. Attributing this kind of failure to the ice load, and then concluding that it is necessary to design for more ice, does not address the real problem. For tower and transmission line engineers to better design structures to withstand the loads imposed by these severe storms, they must not only determine how much ice accreted on structures in a damaging ice storm, they must also determine what initiated the failure in the structures that collapsed.

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1. INTRODUCTION

A severe freezing-rain storm hit Canada and the northeastern United States the week of January 5, 1998. Warm moist air from the Gulf of Mexico encountered cold Arctic air, initially in northern New York and southern Quebec. The cold front moved south and east from there into Vermont, New Hampshire, and Maine. This set up the classic scenario for freezing rain, as the less dense, warm Gulf air was forced up over the Arctic air. The liquid precipitation cooled as it fell through the cold air. When the still-liquid rain and drizzle drops struck a tree or a structure they froze as the latent heat of fusion was removed by convective and evaporative cooling. Ice freezing to trees and overhead lines caused hundreds of millions of dollars of damage in both countries and left hundreds of thousands of people without power for periods ranging from hours to more than three weeks. In the United States the President declared disasters in New York five counties, six Vermont counties, and all New Hampshire and Maine counties except the coast. This ice storm was the worst ever in the experience of many people in upstate New York and northern New England, both in the amount of ice that accreted on trees and structures, and the extent of the storm. The storm footprint extended from Watertown in upstate New York and Dublin in southwestern New Hampshire to Calais in eastern Maine, as well as into the Canadian provinces of Ontario, Quebec, and New Brunswick. (Fig. 1).

The magnitude of the storm inspired superlatives. It has been called a freak storm, the ice storm of the century, and the worst ice storm in 500 years. The damage to trees in the state and national forests has been compared to the 1938 hurricane. The purpose of this report is determine how rare an ice storm like this really is in northern New England. If severe ice storms occur frequently enough, the power and communication infrastructure must be designed to withstand the loads imposed by those storms.

In the next section, publications that specify design ice loads for overhead lines and communication towers are reviewed. The uniform ice thickness that is used to quantify these design loads is defined and described in the third section, along with procedures for determining the uniform thickness from samples of accreted ice. As this is difficult to do, ice loads have rarely been measured in the United States. We have, however, developed ice accretion models that use hourly

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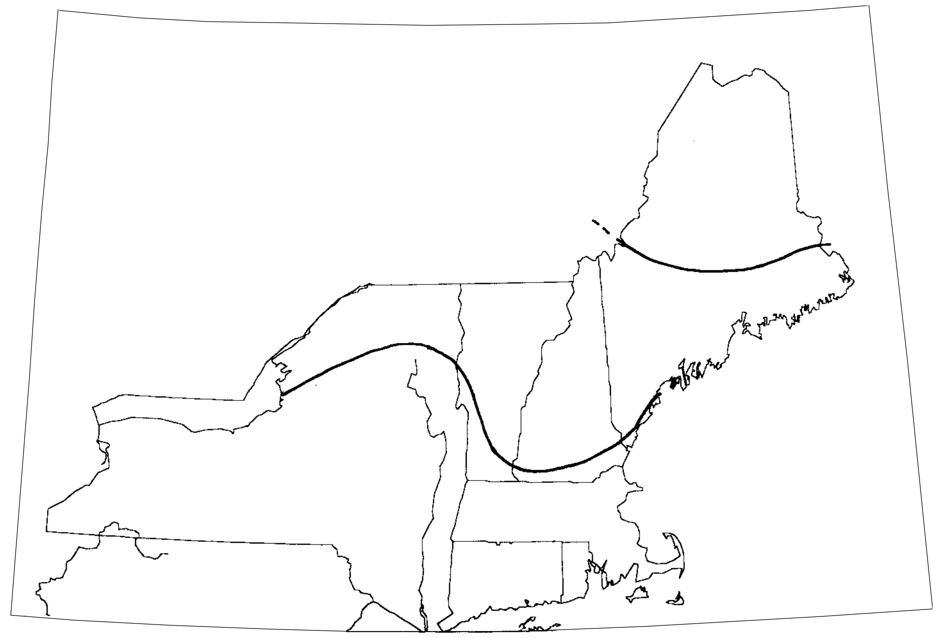


Figure 1. Footprint of the January 1998 ice storm.

weather data to determine ice loads in freezing-rain storms. Those models are briefly described in Section 4, and references to more detailed descriptions of ice load models are provided. In Section 5 a qualitative damage index is described. A number of aspects of the January ice storm are discussed in Section 6: type and degree of damage, modeled ice loads, and comparisons to past ice storms. Where there are measurements or estimates of the accreted ice load, these are compared to the modeled loads. The extreme value analysis method that CRREL has developed for determining extreme ice loads, using the peaks-over-threshold method and superstations, is described in Section 7. Ice loads for a 50-year return period, both from our earlier analysis for the ASCE 7 Standard, *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-98 in prep), and recalculated including ice loads from this storm, are presented. Finally, return periods for the range of severe ice loads that occurred in this storm are determined.

2. APPLICABLE CODES

Communication towers and power lines are designed for ice loads. The applicable code for overhead lines is the *National Electrical Safety Code* (NESC) and the standard for communication towers is the *Structural Standards for Steel Antenna Towers and Antenna Supporting Structures* (EIA/TIA 222-F). For power transmission lines additional guidance is supplied by *Guidelines for Electrical Transmission Line Structural Loading* (ASCE 74). In all these publications ice loads are specified in terms of a uniform ice thickness t, which is applied uniformly to all surfaces of the structure. The ice load, in pounds per foot, corresponding to a design thickness t, depends on the dimensions of the cross section of the component to which the load is applied.

The NESC provides mandatory requirements for the design of overhead lines of all types, including power transmission lines, power distribution lines, phone and cable TV lines, and service drops from the street to houses and commercial buildings. An overhead line consists of a number of subsystems: wires, conductors, and cables that are maintained at the appropriate clear-

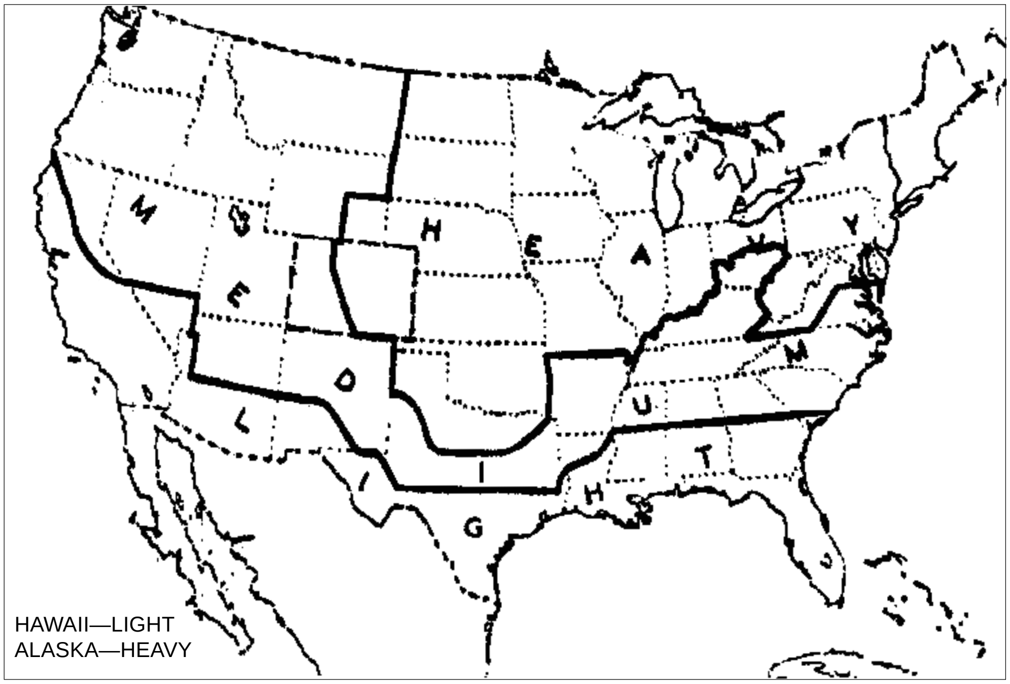


Figure 2. National Electrical Safety Code district map for ice loads: Light 0 in., Medium 0.25 in., Heavy 0.5 in. (NESC 1990).

ances by towers, poles, crossarms, and guys. In power lines, the wires and conductors are isolated electrically from the support structures by single post-type insulators in the low-voltage distribution lines that typically run along streets, or insulator strings in high-voltage transmission lines. The NESC provides design ice- and wind-load maps; however, design-load requirements vary depending on the type of service and the grade of construction. The country is divided into three districts for ice loads: Heavy, Medium, and Light (Fig. 2). In the Heavy loading district, encompassing the region in the United States that was hit by the January ice storm, the uniform ice thickness is 0.5 in. In the Medium and Light districts the uniform ice thicknesses are 0.25 in. and 0 in., respectively. The wind pressures for these districts are 4, 4, and 9 lb/ft^2, respectively. A factor is applied to the basic ice loads that is as high as 1.5 for major transmission lines. Many transmission line designers and utilities recognize that the ice-load district map in NESC shows loads that occur more or less frequently, rather than extreme loads. This is in contrast to the wind-speed map in NESC that shows fastest-mile wind speeds for a 50-year return period, taken from the 1988 revision of *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-88). Thus, on the coast of Maine, for example, utilities are required to design transmission lines to withstand hurricane winds with a 2% probability of exceedance in any year (equivalent to a 50-year return period), but they are not required to design to get the same reliability in their overhead lines when they are subjected to ice loads that occur as often. Because of this discrepancy, some utilities have developed their own more stringent design requirements for ice loads.

The ice-load map that was developed for *Guidelines for Electrical Transmission Line Structural Loading* (ASCE 74) attempted to provide transmission line designers with 50-year return-period loads. These loads, which are also specified in terms of a uniform ice thickness, range from 0 in the extreme southern United States to 1.6 or 2.2 in. in the region hit by the January ice

storm (Fig. 3). A wind speed of 40% of the 50-year return-period fastest-mile wind speed, from ASCE Standard 7-88, is applied with this ice load.

EIA/TIA 222-F is the most recent revision of the standard for communication tower design. It does not provide an ice-load map, but suggests that ice loads be considered in the design of towers where ice accretion is known to occur. Typically 0.5-in. uniform ice thicknesses are assumed. With this ice load a wind speed equal to 87% of the 50-year return-period fastest-mile wind speed from ASCE Standard 7-88 is applied.

The ice-load map in ASCE 74 was developed from a map in a report written by Ivan Bennett in 1959. Bennett used ice thickness data measured by railroad personnel in a study conducted by the Association of American Railroads (AAR) over a 9-year period from 1928 to 1937. He mapped the maximum reported ice thickness in each square of a 60-mile by 60-mile grid laid over the United States (Fig. 4). These thicknesses are probably the maximum ice thicknesses, rather than the equivalent uniform thicknesses, but the report does not provide enough information to determine how the loads were measured or reported. The original records from the AAR study are lost. Hoffmann (1984) developed an ice load map, also based on the Bennett map (Fig. 5), that is significantly different from the ASCE 74 map. These different expert interpretations result from the limited period of the AAR study and the lack of information on the ice thickness measurements that Bennett used.

In 1973 Tattelman and Gringorten developed yet another ice-load map. They used the same Bennett map, but extended the period of record from 9 years to 50 years by using ice thicknesses reported in or estimated from descriptions of severe storms in *Storm Data* (NOAA 1959–present) and its predecessors. *Storm Data* is a National Oceanographic and Atmospheric Administration (NOAA) publication that summarizes destructive weather-related occurrences, including freezing-rain storms, hurricanes, lightning strikes, tornadoes, and blizzards. It has been published monthly since 1959 and each monthly publication is ordered alphabetically by state. Shan and

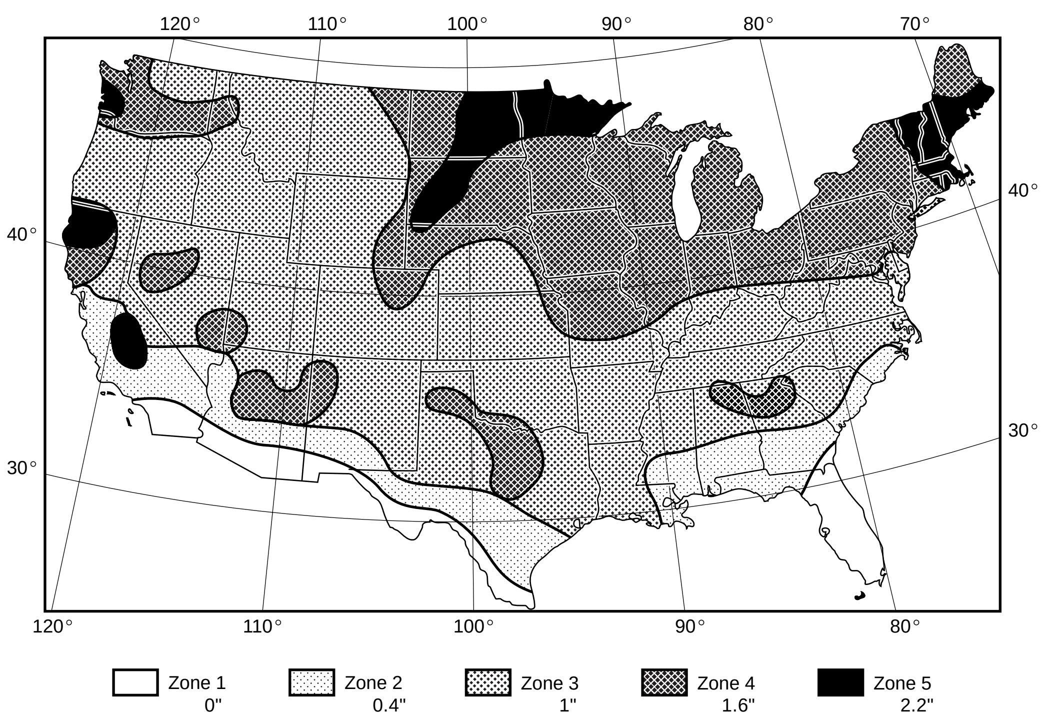


Figure 3. 50-year return-period ice-load map from ASCE 74 (1991).

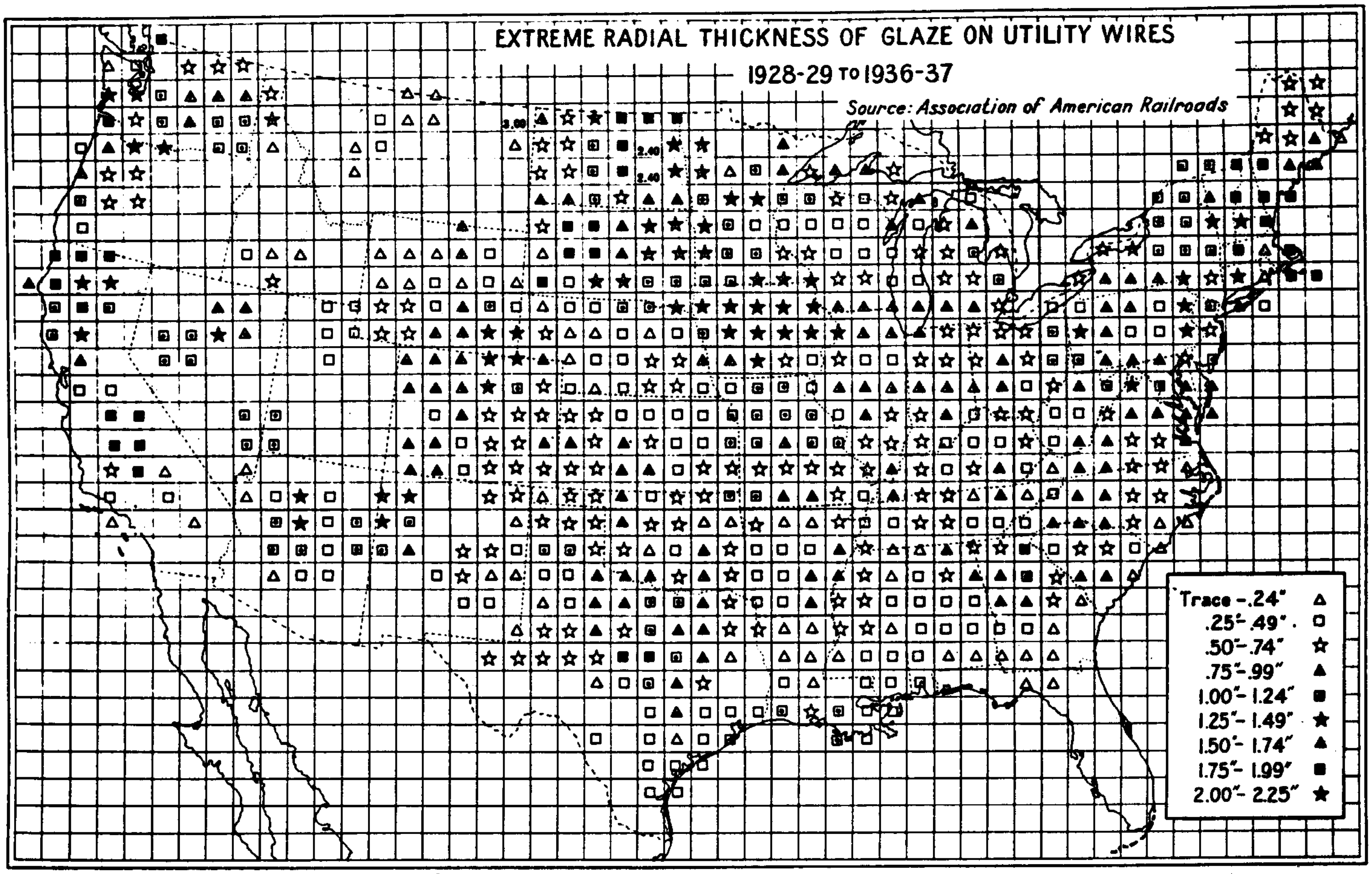


Figure 4. Maximum ice thicknesses measured in a nine-year period from 1928 to 1937. (From Bennett 1959.)

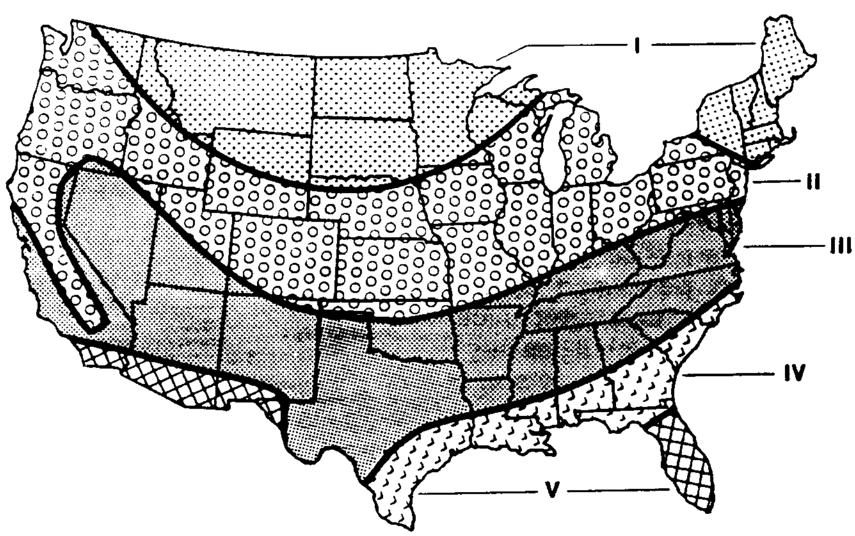
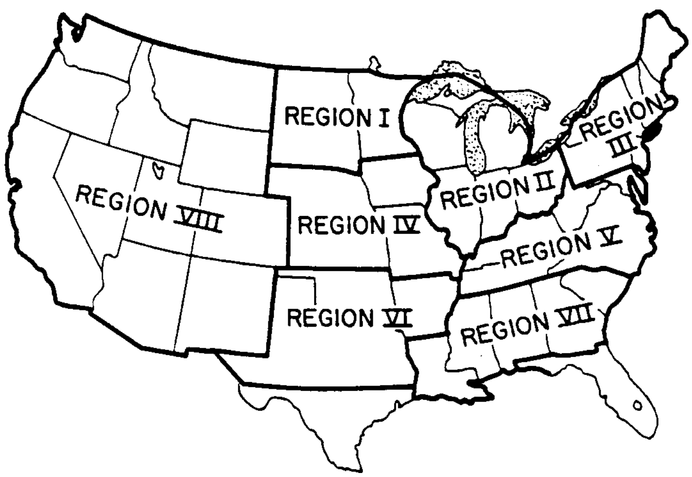


Figure 5. 50-year return-period ice-load map. Uniform ice thicknesses are as follows: District I, 1.5 in.; District II, 1.1 in.; District III, 0.9 in.; District IV, 0.5 in.; District V, 0 in. (From Hoffman 1984.)

Marr (1996) compiled the information on ice storms from *Storm Data* in a database. *Storm Data*'s predecessors, *Monthly Weather Review* (1921–1949), *The Report of the Chief of the Weather Bureau* (1929–1935), *U.S. Meteorological Yearbook* (1936–1949), and *Climatological Data, National Summary* (1950–1959) also included storm information. Tattelman and Gringorten's table of extreme ice loads (Fig. 6) are given as maximum ice thicknesses, rather than the equivalent uniform thickness, in each of seven regions of the country for return periods ranging from 50 to 300 years.

All this information was reviewed by the Ice Load Task Committee for ASCE 7 when it was formed in 1993 to develop a standard for ice loads for ice-sensitive structures, which include overhead lines and communication towers. In the 1995 revision of ASCE 7 the committee chose to include the ice-load map from ASCE 74. For the 1998 revision of the standard we developed a new ice-load map for freezing rain. The draft of ASCE 7-98 is currently in the committee balloting process. After revisions are made in response to the balloting the draft will go out for public ballot and will finally be published at the end of this year. The data, models, and extreme value analysis that were used in developing the map in the draft of ASCE 7-98 are described briefly in Sections 4 and 7.



	Return Period (Years)											
	2		5		10		25		50		100	
Region	AVG	MAX	AVG	MAX	AVG	MAX	AVG	MAX	AVG	MAX	AVG	MAX
I	0.4	1.4	1.4	2.1	1.6	2.4	1.8	5.0	1.9	7.1	2.1	>7.5
II	0.7	1.0	1.4	2.1	1.7	3.3	2.0	5.0	2.2	6.0	2.4	7.0
III	1.2	1.6	1.6	2.4	1.8	3.8	2.0	5.8	2.1	7.2	2.3	>7.5
IV	0.5	1.4	1.4	2.1	1.6	2.4	1.8	5.0	1.9	7.2	2.1	>7.5
V	0.2	1.2	1.2	1.8	1.5	2.2	1.7	2.5	1.8	5.0	2.0	7.0
VI	0	1.0	1.2	1.9	1.5	2.4	1.7	3.8	1.9	5.0	2.1	6.0
VII	0	0.4	0.6	1.8	1.0	2.2	1.3	3.4	1.5	5.0	1.7	6.3

Figure 6. Maximum ice thicknesses (cm) for return periods from 2 to 100 years at representative points (AVG) and at the most severe location (MAX) in each of seven regions of the United States. (From Tattelman and Gringorten 1973.)

3. EQUIVALENT UNIFORM ICE THICKNESS

The ice that accretes on trees and structures in freezing rain varies tremendously in cross-sectional shape. The shape depends on the rate of rainfall; wind speed; air temperature; humidity; the shape, size, color, orientation, exposure, and temperature of the substrate; and on any internal heating. On horizontal surfaces, like streets and sidewalks, the ice will form a uniform layer, perhaps with thicker ice in low areas where the precipitation ponds (Fig. 7). On vertical surfaces, like street signs, some ice will freeze directly to the windward surface, but much of the precipitation will freeze as icicles as it runs down the sign and begins to drip off (Fig. 8). On branches, guys, cables, wires, conductors, angles, and other two-dimensional components, a wide variety of cross-sectional ice shapes have been observed (Fig. 9). Because of this, one cannot compare reported ice thicknesses, both with each other and with the uniform ice thicknesses in the codes, standards, guidelines, and maps that were discussed in Section 2.

Figure 7. Ice on picnic table off Route 11, in northeastern New York, January 8, 1998 (photo Mulherin).

Figure 8. Ice on a sign near Dannemora, New York, January 8, 1998 (photo Mulherin).

We have found that the accreted ice load on two-dimensional objects (branches, wires, angle sections) is best described in terms of the equivalent uniform ice thickness. This can be calculated from either the weight or the volume of ice in a sample. If the ice sample on a wire, for example, is weighed, then

$$t = -\frac{d}{2} + \sqrt{\frac{d^2}{4} + \frac{m}{\pi \rho_i L}} \qquad (1)$$

where t = equivalent uniform ice thickness (cm)
d = diameter of branch (cm)

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a. Crescent on one side (photo Jones).

b. Large accretion on windward side of car antenna (photo Jones).

c. Icicles on wire fence (photo Mulherin).

d. Knobby accretion on Triplex (photo Mulherin).

Figure 9. Examples of ice accretion shapes, January 1998 ice storm.

m = weight of ice (g)
L = length of ice sample (cm)
r_i = density of ice 0.9 g/cm^3
p = 3.14.

Alternatively, if the ice is melted and the volume of water is measured,

$$t = -\frac{d}{2} + \sqrt{\frac{d^2}{4} + \frac{V\rho_w}{\pi\rho_i L}} \qquad (2)$$

where V = volume of melted ice (cm^3)
r_w = density of water 1.0 g/cm^3.

Any consistent set of units can be used in the above calculations. In English units the densities of ice and water are 56 and 62.4 lb/ft^3, respectively.

As Eq. 1 and 2 indicate, the equivalent uniform ice thickness represents the ice load. Because uniformly thick ice forms the most compact ice accretion, t will always be less than the maximum thickness of the ice accretion. The actual load, expressed as the weight of ice per unit length, corresponding to a specified uniform ice thickness, increases with the size, or diameter, of the wire or angle member or branch (Fig. 10). For example, 1-in. uniform ice thicknesses on 0.5-in. wires, 1.5-in. conductors, and 3.5- ¥ 3.5- ¥ 1/2-in. angles weigh 2, 3, and 7 lb/ft, respectively.

In the next section the calculation of ice loads from hourly weather data using ice accretion models is discussed. The derivation of the formula used in the simple model emphasizes the utility of describing ice loads from freezing rain in terms of the equivalent uniform ice thickness.

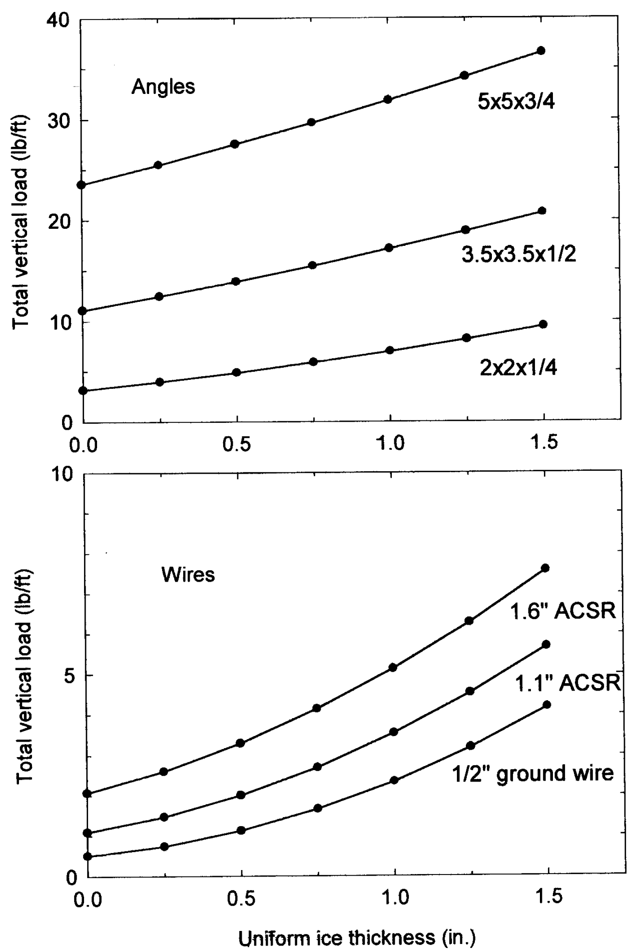

Figure 10. Ice loads in pounds per foot corresponding to uniform ice thicknesses from 0 to 1.5 in.

4. MODELING ICE LOADS

Because ice loads are difficult to measure, they are often estimated by applying ice accretion models to weather data. The weather elements that are required for modeling the accretion of ice in freezing rain are the present weather code, which indicates whether freezing rain is occurring, precipitation amount, and wind speed. Many models also use air temperature and some use dew-point

temperature or humidity, atmospheric pressure, and solar radiation to determine how much of the available precipitation actually freezes to the structure.

The simplest case of ice accreting in freezing rain occurs if all the precipitation impinging on a flat horizontal plate freezes in a uniformly thick accretion. When that happens the amount of ice on the structure is directly related to the amount of rain that falls. For example, if 1 cm of freezing rain falls on a 2-cm-wide flat plate and freezes in place, then a layer of ice $1(r_w/r_i) = 1.1$ cm thick would form. On a 4-cm-wide plate nearby, the same thickness of ice would form with twice the mass. A 2-cm-diameter circular cylinder would intercept the same depth of rain as the 2-cm-wide flat plate. If that water depth is then spread uniformly around the cylinder's circumference and frozen, forming a uniform accretion, then the layer of ice would be $1(r_w/r_i)/p = 0.35$ cm thick. The factor of p is the ratio between the circumference and the diameter of the circular cylinder. Actual ice accretion shapes may vary significantly, from a crescent on the top or windward side of a wire, to little ice on the wire with long icicles underneath. However, the shape of the ice accretion does not have a significant effect on the accreted ice load.

This simple model shows that, at least to first order, the thicknesses of ice on components with the same shape cross section but different dimensions are the same. A slightly more complex model takes the increased flux of water due to the horizontal velocity of the raindrops in the wind into account. Using the flux of precipitation from the falling rain and the wind-blown rain,

$$t = \frac{1}{\pi\rho_i} \sum \left\{ \left(0.1 P_j \rho_w\right)^2 + \left(0.36\, W_j\, V_j\right)^2 \right\}^{1/2} \Delta T \qquad (3)$$

where P_j = precipitation amount in the jth hour (mm/hr)
V_j = wind speed in the jth hour (m/s)
W_j = $0.067 P_j^{0.846}$ (g/m^3)
DT = 1 hour.

The summation is over the number of hours in the freezing-rain storm. W is the liquid water content of the air containing raindrops. This formula for W as a function of the precipitation rate is from Best (1959).

Detailed models for ice accretion include a heat balance calculation to determine the fraction of the impinging precipitation that actually freezes, either directly to the structure, or as icicles as the water begins to drip off. The CRREL model uses temperature, dew point, and solar radiation data with empirical heat transfer coefficients to calculate the heat balance at the accretion surface. As there may not be sufficient cooling to freeze all the available precipitation, the amount of ice accreted by the CRREL model is often less than that calculated by the simple model for the same weather conditions. The CRREL model determines the ice load at the location where the weather data are measured, and the simple model determines the ice load at some hypothetical nearby location with the same amount of precipitation, but colder conditions. These two models are described in more detail and compared with other ice load models in Jones (1996a and b).

In freezing-rain storms other types of precipitation may be mixed with freezing rain. In applying the models we make the conservative assumption that snow and ice pellets mixed with freezing rain freeze to structures as if they were freezing rain. This ignores a) the probably lower collision efficiency and smaller sticking fraction of snow and b) ice pellets bouncing when they hit and thus not sticking to branches and wires.

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5. ICE STORM DAMAGE

The level of damage is a good qualitative indicator of the severity of freezing-rain storms. Both trees and man-made structures differ in their ability to withstand ice loads. In Table 1 is shown our ice-load index that associates different kinds of damage with increasing ice load.

Very slight amounts of freezing rain can cause slippery roads, significantly increasing the driving hazard and causing numerous fender benders and injury accidents. This hazard can be reduced by encouraging people to stay home and by salting and sanding roads. With somewhat

Table 1. Ice load index.

Damage to trees and structures, in order of increasing ice load.
High winds concurrent with the ice load increases the level of damage.

Slippery roads		
Ice on trees shining in the sun		
Outages in the communications and power distribution and transmission systems caused by trees		
Bending birch trees		
Broken branches on susceptible trees		
	Characteristics:	fine branching
		included bark
		brittle wood
		broad or unbalanced crowns
		old or injured trees
	Examples:	poplars
		maples
		beeches
		willows
		trees at edges of a clearing or pruned on one side
Outages to transmission lines caused by galloping		
Broken branches on resistant deciduous trees		
	Characteristics:	coarse branching
		excurrent branching pattern
		narrow crowns
		young, sound trees
	Examples:	oaks
		black walnut
		trees in dense woods
Outages, not caused by trees, in the distribution system		
Broken branches on evergreen trees		
Outages, not caused by trees, in the transmission system		
Communication tower failures		

more freezing rain a thin layer of ice will be visible on trees, making them glisten in the sun, but not causing any structural damage.

The structure of trees and their susceptibility to ice loads are discussed in Heinrich (1997) Hauer et al. (1984), and Burban and Andresen (1994). As the ice load increases, trees with a greater proportion of their mass in small branches and twigs, decurrent branching patterns, and large or lopsided crowns start to bend and break. Birch trees bent to the ground are often an early warning of significant ice loads. Relatively low loads will strip branches off poplars, leaving only the trunk. Tougher deciduous trees with excurrent branching patterns and fewer twigs withstand larger ice loads. Evergreen trees typically suffer the least damage in ice storms. Because their branches are less exposed than the bare deciduous trees, the ice that accretes initially forms a protective shell on the exterior needles and twigs. The ice-loaded branches tend to sag, but they sag onto lower branches that provide additional support. When evergreen branches do break, they are likely to be in trees with widely spaced branches. Trees of all kinds with limited or damaged root systems may topple under an uneven ice load or be blown over by the wind. The number of uprooted trees in an ice storm also depends on the state of the ground. Trees are more easily uprooted in water-saturated, unfrozen soil than in dry or frozen soil.

Any tree damage causes outages in the power distribution system. Distribution lines typically run along streets to distribute electricity from substations to city blocks, suburban neighborhoods, and rural areas. Trees planted along streets and in yards and growing in woods cut through by streets will initially bend under the ice load, causing shorts as they lean against the wires running along the streets and service drops that supply electricity to individual houses. As the ice load increases, the wires and poles are forced to support more broken branches as well as the shock load of heavily iced branches and uprooted trees falling on the wires. Compared to these loads, the ice load on the wire itself is relatively insignificant. These broken trees may pull down service drops, break wires, connectors, and crossarms, and break or uproot poles. Thus, the number and duration of outages in the electrical distribution system is heavily dependent on the amount of tree damage and the proximity of the trees to the wires. Where there are no trees, outages in the distribution system will begin only at relatively high ice loads. The potential of severe tree damage to distribution lines in ice storms has long been recognized. A conclusion in the Executive Summary of a report for the Department of Energy on an investigation of outages as the result of ice storms (Commonwealth Association 1979) was that “[t]he majority of the electric power outages and most utility facility damage...were caused by tree limbs which broke or sagged into electric utility overhead distribution lines.” Their recommendations for reducing the number of outages include more frequent and thorough tree trimming and better planning in the planting of new trees near power lines.

Electrical power is transmitted from where it is generated at a hydro or coal plant, for example, by high-voltage (typically 69-kV up to 735-kV and higher) transmission lines. The large-diameter conductors hang by insulator strings from the crossarms of tall lattice towers, monopoles, wood H-frames, or other structures, to provide sufficient clearance between the tower and the conductors, between the ground and the conductors, and between the different phases. Smaller-diameter static or shield wires at the tops of the towers provide protection against lightning and complete the electrical circuit. Because of resistance in the wires, heat is generated by the electrical current and the conductor may be warmer than the ambient air temperature. There should be very little current in the static wires, so they are at the ambient air temperature. Transmission lines typically run through the trees in a wide right-of-way with the wires above the treetops, so

tree damage is unusual. The low risk of tree damage and the stricter requirements in NESC for both wind and ice loads in the design of transmission lines compared to distribution lines means that damage to the transmission system in moderately severe ice storms is rare. However, lower voltage transmission lines are often on shorter poles in narrow right-of-ways, or near the edge of a wider right-of-way and, thus are more susceptible to tree damage.

Galloping of conductors and guys causes large dynamic loads at low ice loads and moderate, steady winds. The occurrence of galloping was first explained by Den Hartog (1932). Negative lift on the airfoil shape that is formed by a thin layer of ice accreting on one side of a conductor or guy leads to a positive-feedback, low-frequency, high-amplitude oscillation that can tear the attached structure apart. Galloping may continue for days once it begins. A number of devices for reducing the amplitude of galloping, or discouraging its initiation, have been developed and utilities have installed these devices on spans that have been particularly susceptible to galloping. At high ice loads, sustained galloping is less likely because of the weight of the ice-covered conductor and the additional damping from the accreted ice. However, damage to a tower or components of a transmission line from galloping in a minor ice storm may cause failures at ice loads less than the design load in later, more severe storms.

The effect of ice storms on wireless communications systems can be significant (Mulherin 1987). Wireless communications systems include microwave telephone, cellular telephone, personal communications service (PCS) paging, commercial radio and television broadcast, and two-way radio linkage for government agencies, emergency personnel, and businesses. All of these depend upon signal propagation between antennas mounted on tall towers or masts. Problems in ice storms include loss of off-site power and signal degradation from ice buildup on transmitting and receiving antennas. Ice falling from towers is also quite common and can disrupt communications by impact damage to equipment on the ground or on the tower itself and by puncture damage to the roofs of transmitter buildings at the base of towers, which may cause water damage to the equipment inside. Although relatively rare, heavy ice accumulation can also cause towers to collapse. Because these towers are situated in cleared areas and stand well above treetop level, they are not subject to damage from falling trees. Unlike electrical transmission lines, they are usually single towers with no physical attachment to adjacent towers, so that the collapse of one does not typically affect any others. Occasionally, at multi-tower sites, a tower may fall onto and destroy other towers.

Wireless technology is significantly impacted by ice storms but the risk of serious problems can be reduced in a number of ways. To protect against external power loss, critical tower sites often have some source of backup power that will automatically maintain operations when commercial power is interrupted for up to several days. Batteries and diesel- or propane-fueled generators are typical. To protect against falling ice, transmitter buildings at many sites have reinforced roofs or ice guards over the roof. Ice guards or steel screens are often used to protect vital components on the tower itself.

The most serious problem caused by ice accreting is structure overload. Towers are typically well exposed to the weather and are often built on mountaintops. Both mountaintop towers and very tall towers (1000 to 2000 ft) at low elevations may spend hours or days engulfed in low stratus clouds at subfreezing temperatures and thus may be subject to severe loads from in-cloud icing. Very tall towers are engineered considering site-specific loads, including the expected equivalent uniform ice thickness and the concurrent wind-on-ice load. However, smaller towers are often bought “off the shelf,” and may not be designed to withstand severe icing. Towers sometimes collapse in ice storms, causing extended periods of off-air time (Mulherin in press). Providers usually restore at least partial service with alacrity following such a failure because of the highly competitive nature of the communications

industry and the heavy economic losses that accrue when providers go off air. Another incentive is the "good neighbor" image that is gained when commercial broadcasters can stay on the air and switch to emergency community-service broadcasting during a storm.

Cellular telephone technology is rapidly becoming the communication tool of choice and it has greatly improved emergency communications capability. Cellular communications can sometimes be the most reliable communications system during an emergency because they do not require overhead wires that are vulnerable to falling trees. Working in the 800 to 900 MHz range, signal propagation and reception are virtually unaffected by ice accumulation. Of further benefit during periods of emergency operations is an industry practice of reserving certain bandwidths for use during periods of high-volume calling. Cellular systems are composed of line-of-sight networks of towers to carry the signal. The loss of signal from any tower will result in lost communications capability in all service areas farther down the network. All sites generally have battery backup that will keep the site operating for 8 to 20 hours in the event of external power loss. Sites that are major hubs in the cellular network are usually backed up with auxiliary generators that are generally configured to start up automatically when power is interrupted. If external power is restored before batteries or fuel run out, no interruption in service occurs.

Falling ice is a more common problem for cellular and microwave systems. Both require meticulous antenna alignment to maintain tower-to-tower transmission integrity. Ice impact on tower components could easily disrupt this alignment enough to sever communications. However, ice guards can usually prevent all but the heaviest ice impact from disrupting service. Cellular providers often lease space for their equipment on existing towers, in which case new structural loads are determined to ensure that tower modifications meet current design standards. Self-supporting towers are favored by cellular and PCS providers, because they require less area and lower maintenance. They are less sensitive to extreme icing conditions than guyed structures and hence have a lower risk of collapse. However, when designed for the ice conditions occurring at a site, both types of towers will perform satisfactorily.

The damage index in Table 1 is by no means absolute. Even moderate winds increase the damage to ice-covered trees and structures by combining a significant lateral load with the already high vertical load. The overall health and age of trees and any past damage may increase their susceptibility to ice loads. For man-made structures the age, design loads, and load combinations considered in design, factor of safety, maintenance history, and failure containment provisions all influence the risk of failure, as well as the extent of the failure, of a particular overhead line system or network of communication towers.

6. THE JANUARY 1998 ICE STORM

The ice storm caused extensive damage to trees, long outages in the electrical distribution system, communication problems, transmission line damage and outages, and the failure of communication towers. In this section we discuss the level of damage, the ice loads that caused that damage, and the history of severe ice storms in the northeastern United States.

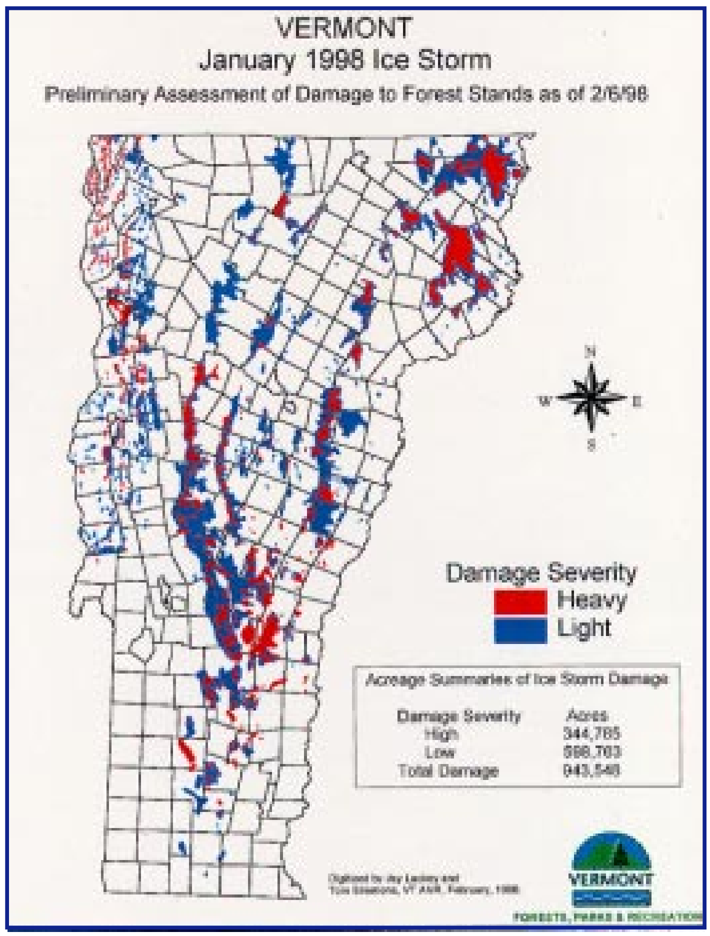
6.1 Damage

6.1.1 Trees

This ice storm damaged trees, many of them severely, over all three states covered by the Region 1 disaster declaration as well as in New York and the neighboring provinces of Quebec,

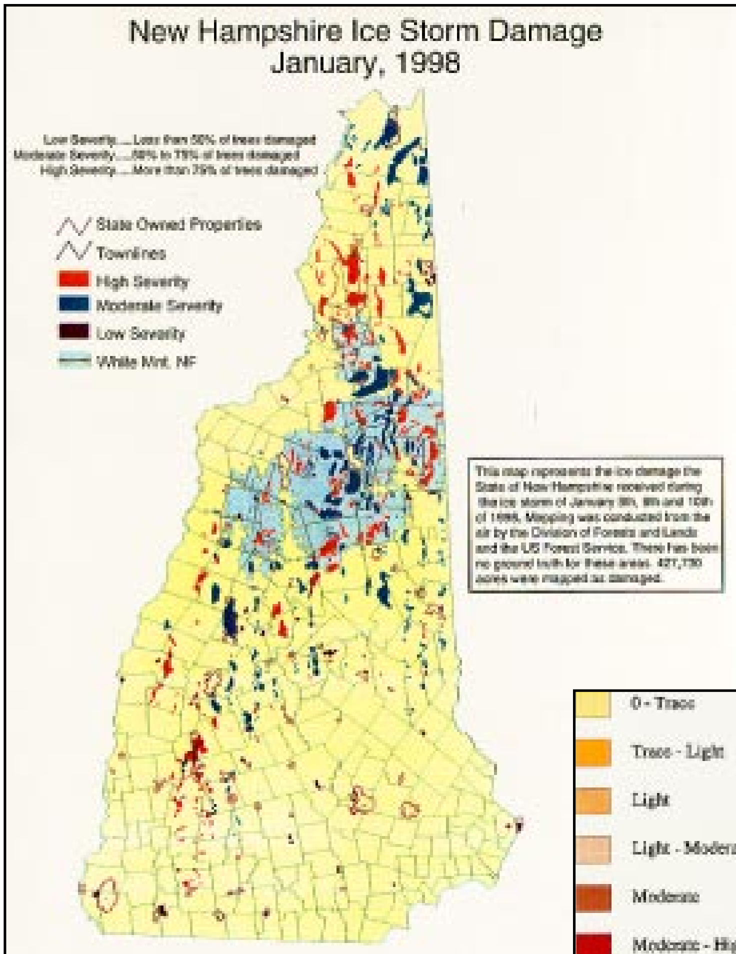
Ontario, and New Brunswick in Canada. The level of tree damage has been compared to the 1938 hurricane. Forestry organizations in New Hampshire, Maine, and Vermont have coordinated their aerial and ground surveys to map the extent and severity of damage to the national forests, state forests, and privately owned woodlots and sugar bushes. They are compiling and organizing the information into a single database managed by the U.S. Forest Service, Northeastern Area GIS Group in Durham, New Hampshire. In general, the greatest damage occurred to hardwood stands, while evergreen stands withstood the ice loading. The information on forest damage that follows contains information and general observations from telephone and personal contacts that we made with these groups. We show in Fig. 11a, b, and c maps of forest damage in Vermont (Vermont Department of Forest, Parks and Recreation unpublished), New Hampshire (New Hampshire Division of Forests and Lands, Forest Health Protection Section and U.S. Forest Service Northeast Area GIS Group unpublished), and Maine (Maine Forest Service unpublished). The mapped damage severity is based primarily on aerial surveys and will be revised and refined using ground surveys that are now underway. Questions on the maps should be addressed to the referenced agencies. To determine general trends in the forest damage, we also compiled information obtained from hiking and snowmobile clubs, reports from trail users that are posted at the clubs' Web sites, and information from local residents.

In Vermont, an extensive forest damage assessment was completed by the Green Mountain National Forest (GMNF) and the Vermont Department of Forest, Parks and Recreation (VDFPR), who compiled the damage information into the map shown in Fig. 11a. Other sources of forest damage information are the Green Mountain Club, the Appalachian Trail Conference, the Catamount Trail Association, and the Vermont Area Snow Travelers (VAST). Forest damage in Vermont was spotty both in location and in severity. Officials of the GMNF reported that east-facing slopes and the tops of ridges at elevations above 2000 ft generally suffered the worst damage, especially in its Rochester District, near the center of the state. The general trend over the entire state, according to VDFPR officials, is that the lighter damage began at around 1300 ft and escalated to heavy to severe damage starting at about the 1800-ft level, except around Lake Champlain in the northwestern corner of the state. There, cold air at lower elevations resulted in the heaviest ice loads

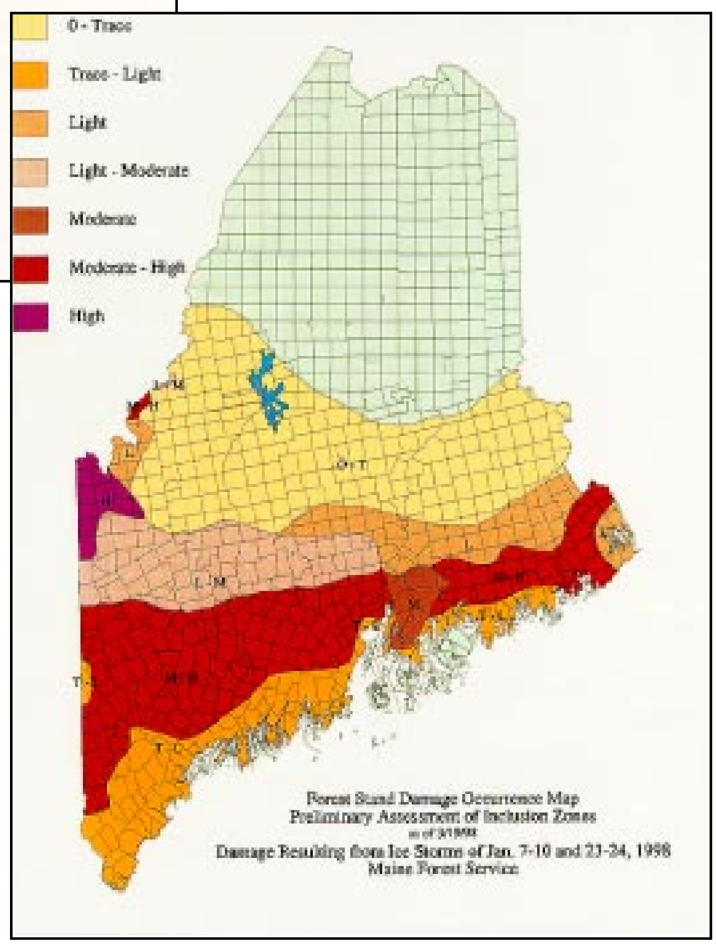


a. Vermont.

Figure 11. Maps of damage to forests from the January 1998 ice storm.



b. New Hampshire.



c. Maine.

Figure 11 (cont'd). Maps of damage to forests from the January 1998 ice storm.

and extensive tree damage at and near lake level. Outside that area the boundary separating light and heavy damage trended toward higher elevations farther north in the state. Icing apparently did not extend above about the 3000-ft level. Fig. 12a shows the tree damage at 1830 ft between Randolph and Bethel. Farther east along this road, at elevations below about 1660 ft, trees were not damaged. Damaged trees near Starksboro (750 ft) in western Vermont are shown in Fig. 12b. On Mount Philo, south of Burlington in the Champlain Valley, even conifers were severely damaged. Mount Philo rises about 500 ft above the surrounding terrain, to an elevation of 800 ft, with a steep west-facing slope. Damage to red pines at the base of this slope is shown in Fig. 12c. Oaks and scotch pines growing on the northeast-facing terrace on the top of Mount Philo were also severely damaged. Tree damage farther north near Lake Champlain is shown in Fig. 12d and e. The photo in Fig. 12d was taken on January 8 at 8:50 a.m. near Swanton, Vermont at an eleva-

a. Along the road between Randolph and Bethel at 1830 ft (photo Jones).

b. Near Starksboro (photo Jones).

Figure 12. Tree damage in and near Vermont.

c. Mount Philo at 400 ft (photo Gary Salmon, VDFPR).

d. Near Swanton at 100 ft (photo Jones).

e. Two miles west of Lake Champlain near Beekmantown, New York, at 200 ft (photo Mulherin).

Figure 12 (cont'd).

tion of 100 ft. That damage occurred with an ice load of 0.2 in. (Throughout this report we report ice loads in terms of the equivalent uniform ice thickness, as described in Sections 3 and 4.) The damaged trees in Fig. 12d were photographed at 11:15 a.m. on January 8 at the Beekmantown rest area on I-87 in New York, just north of Plattsburgh, two miles west of Lake Champlain at an elevation of 200 ft. The damage was caused by an ice load of 0.5 in.

In New Hampshire, forest damage assessments similar to Vermont's were completed by the White Mountain National Forest (WMNF) and the New Hampshire Division of Forests and Lands (NHDFL). The information was compiled by the U.S. Forest Service Northeastern Area GIS Group, in the map shown in Fig. 11b. Preliminary ground surveys have indicated that the

outlined areas indicated on this map as low damage severity should actually be included in the moderate damage severity category (Laura Boffinger, personal communication). Other sources of information that we used to summarize elevation ranges for ice damage in New Hampshire are the Appalachian Mountain Club, the Appalachian Trail Conference, and local residents. The NHDFL reported that the lower elevation limit for significant icing was at about 1200 ft south of the White Mountains. In the White Mountains National Forest the lower limit of ice damage decreased from about 2000 ft in the southern White Mountains to 1600 ft in the northern White Mountains. The upper limit of ice damage is at about 4000 ft, indicating that these higher elevations were in the warm air layer. Above the halfway point on the Mount Washington auto road there was no ice on January 9 (Mark Twickler, personal communication). It was estimated that between 10 and 15% of the Forest's 750,000 acres was impacted, with the heaviest damage occurring in the northern portion of the Forest. North of the White Mountains, the lower elevation of ice damage to trees was at 900 ft on east-facing slopes and 1700 ft on west-facing slopes. Some reports from around the state noted that the most damage occurred on eastern or southeast facing slopes, while in other areas no directional differences were apparent. Examples of tree damage in New Hampshire are shown in Fig. 13a through g, generally from south to north across the state. The ice-covered trees in the photo in Fig. 13a are along the road between Harrisville and Dublin. The elevation of the road between those towns ranges from 1300 to 1650 ft. The damage shown in Fig. 13b occurred in Bradford at an elevation of 1250 ft, while lower elevations escaped the ice. An example of the tree damage in New London (1300 ft), which was hard hit by the storm, is shown in Fig. 13c. Nearby, at higher elevations in Enfield, the ice loading was severe. A uniform ice thickness of 0.7 in., measured on January 12, caused the damage shown in Fig. 13d at 1660 ft. In New Hampton Jamie DiFillippe (personal communication) described light tree damage beginning at 900 ft, with the landscape at 1200 ft looking like a "total disaster" with maple trees split down the middle, but little damage to evergreens. In the Lakes region, there was tree damage, for example, in Wolfeboro at 540 ft (Fig. 13e) and near Ossipee at 900 ft (Fig. 13f). Farther north, there was no ice on the summit of Cannon Mountain (Bert Davis, personal communication) or on Mount Washington above about 3600 ft, but at lower elevations on the mountain above 1800 ft, ice caused the damage shown in Fig. 13g. Northwest of Berlin in the Kilkenney Area of the White Mountain National Forest at 1640 ft, ice brought down trees, which knocked out power and blocked roads to the fish hatchery (John Farr and Royce Benedict, Berlin Fish Hatchery, personal communication).

In Maine the forest damage assessment was undertaken by the Maine Forest Service. Its map (Fig. 11c) shows seven levels of damage severity. The levels are defined by the percent of affected trees: a) trace, 1 to 5% breakage, b) light, 6 to 20% breakage, c) moderate, 21 to 50% breakage, and d) high, over 50% breakage. Two regions with trace-to-light damage, primarily along the coast, total 1.6 million acres. Ice loads caused moderate damage and moderate-to-high damage just inland of this region, over 3.8 million acres. Even farther inland, light and light-to-moderate damage occurred over 2.8 million acres. There was high damage to 0.3 million acres in the northwestern corner of the state, while 4.7 million acres had only trace damage or less. Examples of tree damage in the storm are shown in Fig. 14a through e. Ice accumulation damaged trees in Minot (330 ft) shown in Fig. 14a. At an elevation of 400 ft in Gray, north of Portland, there was extensive tree damage (Fig. 14b) caused by ice loads approaching 1 in., while in Portland itself there was very little ice. The region around Augusta was hard hit by the storm (Fig. 14c). The ice load that bent the birch trees to the ground in Fig. 14d, between Mount Ver-

a. Between Harrisville and Dublin at about 1500 ft (photo Nick Collins).

b. Bradford at 1250 ft (photo Jones).

c. New London at 1300 ft (photo Kathy Lowe-Bloch).

Figure 13. Tree damage in New Hampshire.

d. Enfield at 1660 ft (photo Mulherin).

e. Wolfeboro at 540 ft (photo Jones).

f. Berlin at 1640 ft (photo Mulherin).

g. Mount Washington (photo Eric Meyerson, UNH).

Figure 13 (cont'd). Tree damage in New Hampshire.

non and Vienna, was about 0.2 in. at an elevation of 500 ft. East of Bangor near Deblois ice loads of about 1 in. damaged the trees shown in Fig. 14e. The northern 40% of the state had frozen precipitation in the form of ice pellets throughout most of the storm. Heavy loads on flat and low-pitched roofs in this region were from the accumulation of ice pellets from this storm on top on previously fallen snow. However, even in regions where the precipitation at lower elevations was in the form of ice pellets, at higher elevations the raindrops may not yet have frozen and there could be local damage from freezing rain in higher terrain.

a. Minot at 330 ft (photo Mulherin).

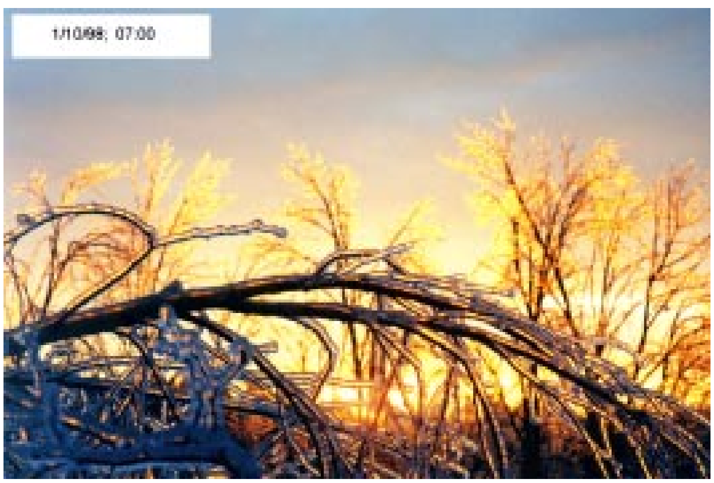
b. Gray at 400 ft (photo John Jensenius, NWS).

Figure 14. Tree damage in Maine.

6.1.2 Distribution system

Damage to power distribution lines, which serve individual houses and businesses, occurred throughout the region hit by the ice storm. Distribution lines were damaged primarily by trees leaning on the wires and by broken branches and trees falling on wires, pulling the wires down or breaking crossarms or poles. (Fig. 15). Because a) homeowners and municipalities plant trees and resist tree trimming and removal for aesthetic reasons, and b) trees are ideal collectors of ice, distribution line outages often occur early in an ice storm. These outages tend to be long-lasting because a) damaged trees must first be removed to gain access to the downed line and b) all portions of a circuit must be repaired before any customers on that circuit can be brought back on line. In the rural areas in Maine, New Hampshire, and Vermont, where miles of distribution line may serve only a few customers, outages were prolonged. The number of customers without power and the duration of outages because of problems in the power distribution system are likely to be closely tied to the closeness of the association between people and trees in the region and the extent of the storm, rather than with the magnitude of the ice load. An evaluation of the outage pattern in the distribution systems in all three states might identify districts in which additional

c. Near Augusta (photo Central Maine Power).



d. Between Mount Vernon and Vienna at 500 ft (photo Bill Duffy, Geomantics).

e. Near Deblois (photo Jones).

Figure 14 (cont'd). Tree damage in Maine.

tree clearing, better tree pruning practices, or a program to remove danger trees would lead to greater reliability of the distribution system in future ice storms of any severity.

The Public Utility Commission in Maine collected distribution outage information from Central Maine Power (CMP) and from Bangor Hydro. Central Maine Power provided tables listing the number of outages each day in each of its districts, along with the number of customers in each district. The severe damage to its system is summarized in the map in Fig. 16, which shows the percentage of its customers without power in each district at the peak of the ice storm. Information provided by Bangor Hydro, tables listing the average duration of outages reported by cus-

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a. Near Augusta, Maine (photo Central Maine Power).

b. Champlain, New York (photo Mulherin).

15. Examples of damaged distribution lines.

tomers for each street in each city in its service area, cannot be readily summarized to provide a snapshot of the effect of the storm in its service area. Its personnel attributed the relatively lighter damage to its system to its recently implemented effective tree clearing program (Jeff Fenn, Ken Miller, and George Baker, personal communication). Eastern Maine Electric Coop, based in Calais, had distribution outages to about half of its customers that took up to a week to repair (Charles McAlpin, Eastern Maine Electric Coop, personal communication). The weight of the ice on wires and falling ice-laden branches and trees brought down wires and broke 80 poles. Outages occurred from Topsfield south to the southern boundary of its service area, which runs along Route 9 east to Calais on Passamaquoddy Bay. North of Topsfield the bulk of the precipitation fell as ice pellets, which accumulate on the ground, but do not stick to trees and wires.

Some New Hampshire utilities were hard hit by the ice storm, while others escaped the brunt

of the storm and had very little damage to their system. New Hampshire Electric Cooperative (NHEC), with a service area spread all over the state but concentrated in central New Hampshire, was hardest hit in the Ossipee and Alton areas (Sharon Yeaton and Henry Lynch, NHEC, personal communication). Falling trees broke many poles and caused the worst damage to its system on record. Public Service of New Hampshire's (PSNH) distribution system was hit hard in the Monadnock region, Hillsborough, greater New London, and the Lakes region into Conway and Rochester, with a total of about 55,000 outages (CATV 1998). Granite State Electric had some problems in its service area east of the Connecticut River, but the relatively light damage to its system allowed it to help neighboring utilities recover from the storm (Richard Holmes, Granite State Electric, personal communication). Exeter and Hampton Electric, with a service area covering thirteen towns near the seacoast, saw minimal ice loads and had no problems in its system (Ray Letourneau, Exeter and Hampton Electric, personal communication). Concord Electric's problems were confined to Webster and Boscawen, where broken trees and branches caused outages to fewer than 10% of its customers (Eric Werner, Concord Electric, personal communication).

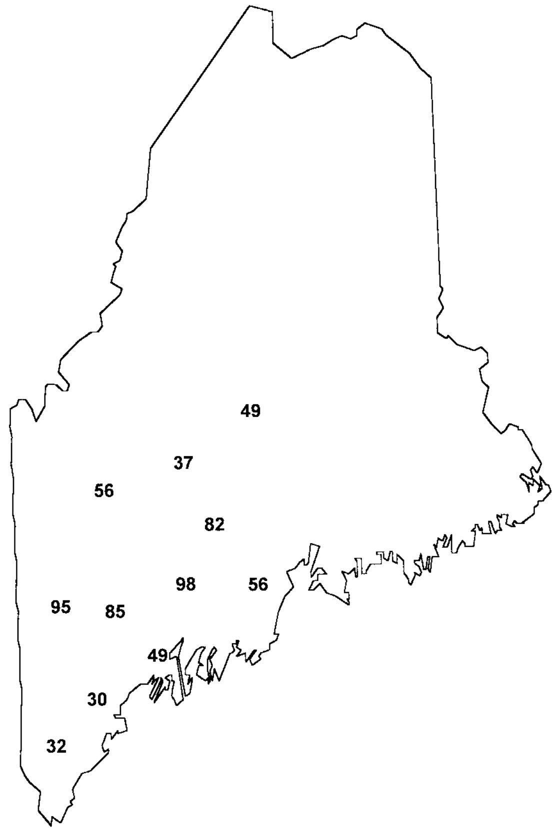

Figure 16. Central Maine Power outages at the peak of the January 1998 ice storm.

The worst damage in Vermont was in the northwest corner of the state (Tom Dunn, Public Service Department, personal communication). Outages in Central Vermont Public Service's (CVPS) distribution system began on January 7 and all customers were back on line by January 13. Twenty-thousand customers were affected in its service area, which covers most of southern and central Vermont, the regions around St. Johnsbury and Burlington, as well as towns in Vermont and New Hampshire in the Connecticut River valley (Jack Crowther, CVPS, personal communication). Repairs were most time-consuming in heavily wooded areas in difficult terrain. The tree damage to CVPS's distribution lines was the worst in thirty years. Damage to Green Mountain Power's (GMP) distribution system totaled $2,000,000 (Dottie Schnure, GMP, personal communication). The ice load on Citizens Utilities' wires was three times any load experienced in the past (Steve Guyette, Citizens Utilities, personal communication), with much heavier ice loads, and more damage to its distribution system, in the region around the north end of Lake Champlain, than in the Grande Isle region farther south.

6.1.3 Transmission system

While trees leaning or falling on wire cause problems in electric power distribution systems, tree problems are less common in the electric power transmission system because the wires are on taller poles in right-of-way clear-cuts. Thus transmission system outages are likely to be good indicators of severe ice and wind-on-ice loads on the wires and conductors.

The only severe transmission line outage in Vermont occurred near the Canadian border. The 46-kV line on the causeway over the Missisquoi Bay between West Swanton and Alburg was down for several days. The weight of ice caused two poles and between 40 and 50 crossarms to break. Ice-laden trees caused two other 46-kV lines to trip out at times during the storm (Doug Best, CVPS, personal communication). One of these went from New Haven to Lincoln and the other from Middlebury to Weybridge.

In New Hampshire a single non-tree-related problem in the transmission system occurred to the 450-kV DC line (designed for 1.5 in. of ice) where it crosses the summit of Sentinel Mountain at about 2100 ft in Warren (Richard Holmes, Granite State Electric, personal communication). The ice load on a static wire caused the pin in a Y-shackle to pull out and the wire to drop. The line was subsequently brought back up at two-thirds power before the location of the break was found and repaired about two days later. Metallurgical tests on the Y-shackle indicated that its performance was within the specified strength tolerance limits. David Plante, Reggie Lang, and Kevin Cote of Public Service of New Hampshire (PSNH) supplied information on outages in PSNH's 2000 miles of transmission lines all over the state. PSNH experienced a number of tree-related problems to its 34- and 115-kV lines, which are in fairly narrow right-of-ways. In New Hampton it lost eight to ten sections of a 1920s vintage line. The two problems in its 115-kV system were caused by tall white pines, well out of its right-of-way, falling on the wires. Its transmission lines are designed to NESC, except the 345-kV lines, which are engineered to withstand 1.5 in. of ice, in addition to the NESC-specified loads.

In Maine, Bangor Hydro's 115-kV line east of Deblois failed (Ken Miller, Larry Billings, Jeff Fenn, George Baker, Bangor Hydro, personal communication). That radial line, built in 1955, is the only line serving the Calais region in eastern Maine. The cascade failure of six miles of H-frame structures (Fig. 17) was initiated by a single conductor breaking from the heavy (~1 in.) ice load. The cascade was stopped at one end by a corner tower, and at the other by a long span that absorbed the load. Power was restored to the region, while a new line was under construction, by routing electricity along existing 33-kV lines, and using local generation (diesel and wood). There were a number of problems in CMP's power transmission system, primarily in its 34-kV system, with only a few problems in the 115-kV system (Tom Bragg, CMP, personal communication). The 34-kV lines are particularly vulnerable to tree damage, because the wires are on relatively short poles (35 to 40 feet tall), and the lines are in narrow right-of-ways or near the edge of wider right-of-ways for 115-kV lines. As redundancy is incorporated in the system, many of the problems caused no outages. Other outages, generally limited to four hours, occurred during switching or sectionalizing of a line. There were, however, a

Figure 17. Six miles of Bangor Hydro's 115-kV H-frame transmission line in the blueberry barrens east of Deblois failed under the ice load (photo Larry Billings, Bangor Hydro).

Table 2. Summary of CMP transmission outages.

Cause of outage	Number of occurrences
Trees	23
Broken post-type insulator	11
Broken crossarm	8
Conductor down	5
Broken pole	3
Entire structure down	3
Underground cable fault	1
Miscellaneous (burnt pole, tap burnt off, bus fault, broken aerial, broken pin insulator)	5

number of failures that resulted in prolonged customer outages. The causes of all these outages are summarized in Table 2. Post-type insulators typically break from the dynamic load induced when ice unloads suddenly from the wire. In all other cases, except the underground cable fault, ice-laden trees and branches falling and leaning on the wires initiated the damage that caused the outage. In eastern Maine, an ice-damaged switch caused a nine-hour transmission outage in Eastern Maine Electric Coop's system that affected about 40% of its customers.

6.1.4 Communications

Our assessment of the wireless communication system in the storm-affected region indicates a generally positive performance of the system as a whole. Major problems included insufficient auxiliary generators to power all the sites that were without commercial power for an extended period, difficulty in getting fuel to the sites with generators because of the trees blocking access roads, and cracked dish and cellular antennas. In most areas problems were addressed relatively quickly to regain some level of service. Successful solution of problems was accomplished by a combination of the following:

1) Auxiliary power sources, including batteries and generators
2) Backup antenna sites
3) System redundancy (alternate ways of bypassing off-line towers)
4) Excellent cooperation within the industry
5) Providers having an adequate parts inventory or the means to buy or borrow on short notice.

To date we have confirmed the collapse of 8 broadcast and 10 two-way towers throughout the storm-affected region (Table 3). We know of no communication tower failures in Vermont and only one in New Hampshire. The WLNH-FM radio station lost its 245-ft-tall tower in Laconia (Fig. 18a). The tower, a key station in New Hampshire's EAS system, also carried the antenna for FM radio station WBHG, which was off the air for 11 days. The bottom half of the WEZQ tower that failed in the storm is shown in Fig. 18b. At this site on Blackcap Mountain in East Eddington, Maine, a dozen other towers withstood the ice storm. The locations of the confirmed tower failures are shown in the map in Fig. 19.

On many of these towers very large ice accretion estimates are reported under Comments in Table 3. A photo taken of the ice on the guys of the Coast Guard tower on Cadillac Mountain in Acadia National Park supports the reported 8- to 10-in. ice diameter on a 1/4-in.-diameter guy. The probable mechanism for the formation of the large ice accretions on towers on these mountaintop sites is discussed in Section 6.2.

Phone drops that were pulled off houses by falling trees and branches were the major problem for non-wireless phone systems. In contrast to electrical distribution wires that run along

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Table 3. Communication tower failures during the January 5–10 ice storm.

CONFIRMED TOWER FAILURES	LOCATION	TOWER HEIGHT (ft)	GROUND ELEV. (ft asl)	COMMENTS
Atlantic Communications 2-way & paging	Dedham, ME N44-45-30 W68-34-00	120	960	Sliding ice on guys; ice on 5/8-in. guys estimated 8 in. in diameter
Industrial Communications 2-way	Falmouth, ME N43-45-35 W70-19-15	~150	510	
Limerick Fire Dept 2-way	Cornish, ME N43-45-00 W70-46-50	130	1320	Ice on 1/4-in. guys estimated 5 in. in diameter
PCT Communications 2-way	Topsfield, ME N45-22-30 W67-48-20	90	1238	Top 60 ft broke off
Piscataquis County Sheriff Dept 2-way	Dover-Foxcroft, ME N45-13-00 W69-14-40	100	698	Ice on 1-in. tower leg estimated 5 or 6 in. in diameter
US Coast Guard and Acadia National Park 2-way	Bar Harbor, ME N44-21-00 W68-13-40	60	1582	Ice on 1/4-in. guys estimated 8 to 10 in. in diameter
WBFB-FM	Frankfort, ME N44-34-51 W68-53-51	283	1000	Ice on guys estimated 3 in. thick
WCDQ-FM	Sanford, ME N43-25-06 W70-48-06	240	680	Ice on guys estimated 5 in. thick
WEZQ-FM	E. Eddington, ME N44-45-30 W68-34-00	140	1000	Guys failed, top half of tower fell
WKZS-FM WHTH-FM backup New Gloucester Fire Dept	New Gloucester, ME N43-57-10 W70-17-40	500	500	Top half of tower fell; ice on guys estimated 4 to 5 in. thick
WLNH-FM	Laconia, NH N43-35-50 W71-29-50	245	850	
WCIZ-FM	Watertown, NY N43-57-20 W75-50-25		1000	
WTNY-AM	Watertown, NY N43-56-40 W75-56-50		445	
WUZZ-AM	Watertown, NY			
Four 2-way towers	Watertown, NY N43-58 W75-55			
UNCONFIRMED TOWER FAILURES				
Cellular tower	Watertown, NY			

a. WLNH tower in Laconia, New Hampshire (photo Mulherin).

b. WEZQ tower in East Eddington, Maine (photo Mulherin).

Figure 18. Communication tower damage.

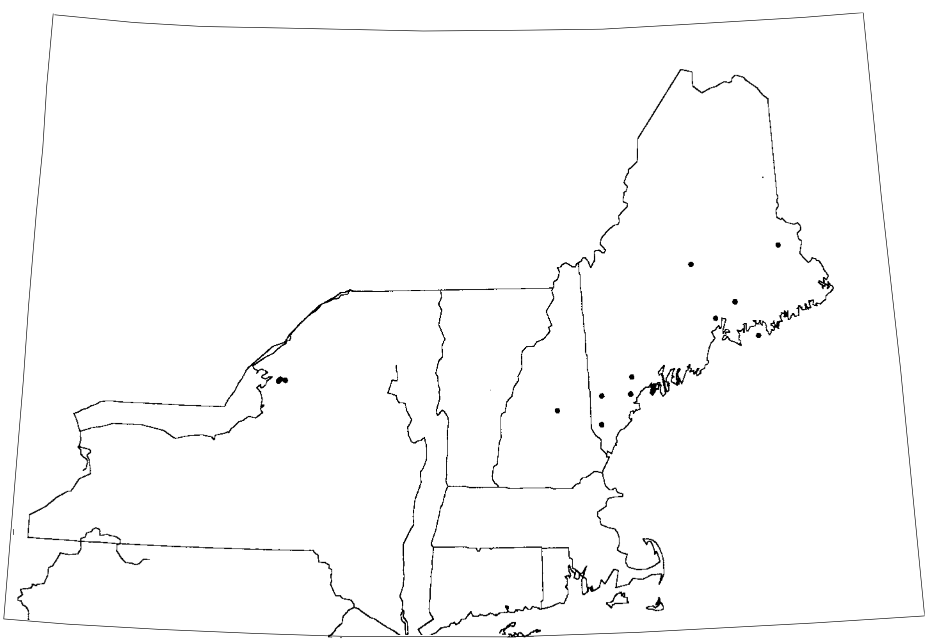

Figure 19. Locations of confirmed communication tower failures in the January 1998 ice storm.

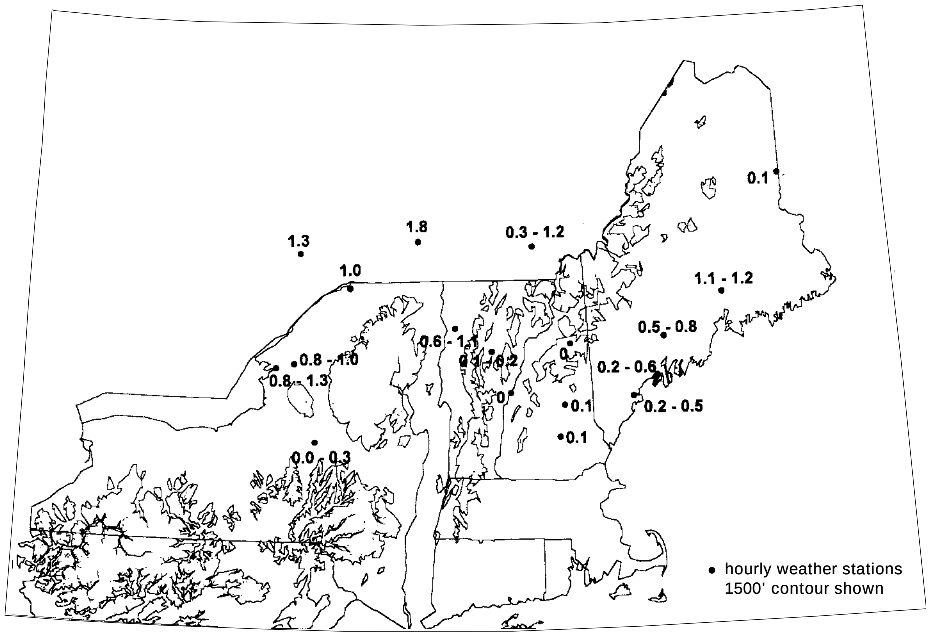

Figure 20. Ice loads at weather stations in the United States and Canada in the January ice storm.

streets, phone wires still work when a tree is leaning on them, or even when they are on the ground, as long as the wire is not broken.

6.2 Ice loads

We modeled ice loads in this storm using hourly weather data at stations in Canada, New York, Vermont, New Hampshire, and Maine, using both the CRREL model and the simple model. Our results are shown in Fig. 20. Where a range of ice loads is shown, the lower load is from the CRREL model and the higher load is from the more conservative simple model. A single value indicates that the temperature was cold enough that the results from the two models are the same. The 0.1-in. ice load in Laconia was measured by Russ Hobby at his weather station on a 3/4-in.-diameter horizontal rod. The AWOS weather station at the Laconia airport was out for most of the storm, so the weather data we have included from Laconia is from Mr. Hobby's station. In Montreal the weather data showed 1.4 in. of precipitation falling in a six-hour period in the morning of January 10, with the present weather codes for those six hours indicating no precipitation and an air temperature of 36°F. In modeling the ice load there, we have assumed that this precipitation actually occurred during the storm, but was not measured until the 10th when the temperature went above freezing. We did not see apparently late-measured precipitation at any other stations. The highest modeled loads are in Canada, particularly Montreal, and in upstate New York. No freezing rain was observed at the summit of Mount Washington (6200 ft) or near the Connecticut River in Hanover, New Hampshire (500 ft), where there was plenty of rain, but the temperature was above freezing. In Houlton, Maine, on the other hand, the cold air layer was too thick and cold for freezing rain and most of the precipitation fell as ice pellets. The map in Fig. 21 shows the amount of precipitation at each site between January 5th and 10th, again including the late measurement of 1.4 in. of precipitation in Montreal. There was less precipitation in the southeastern portion of this region during the ice storm than elsewhere in the region.

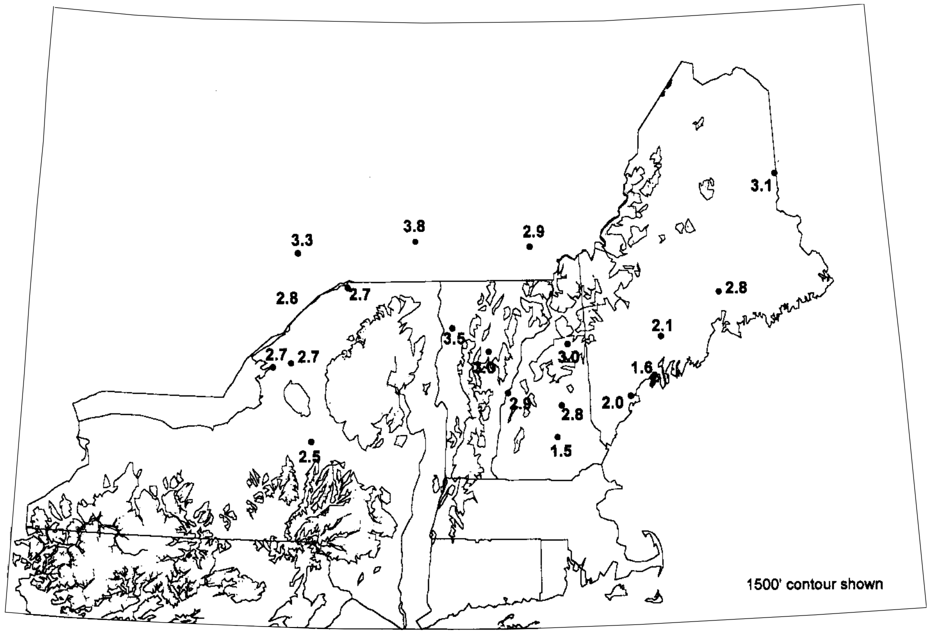

Figure 21. Total precipitation at weather stations in the United States and Canada between January 5 and 10.

As freezing rain often occurs with temperatures very near freezing, the geographical distribution of icing may be associated with elevation in hilly or mountainous regions. Thus the ice loads from the two weather stations in Vermont, the four in New Hampshire, and the five in the region of interest in Maine cannot be easily extrapolated to the rest of those states. In this storm, in the rough terrain in Vermont, New Hampshire, and Maine, it appeared that lower elevations were generally too warm for the rain to freeze, while at higher elevations the air was colder. There were sites where the temperature was 33°F with the precipitation falling as plain rain, while a half-mile away and 600 feet higher, freezing rain falling at an air temperature of 31°F coated trees and structures with ice.

To estimate the effect of elevation in the mountains on the accreted ice load, we used the weather station data from stations in the region and decreased the air temperature in 1°F increments to simulate the temperature decrease that occurs with elevation increments of 280 ft in the Standard Atmosphere (Batchelor 1962). We do not attempt to include in this simulation the probably higher winds at higher elevations, because the wind speed is affected by topography, as well as by elevation. As the flux of precipitation increases with wind speed, windy sites that are also cold enough will experience more severe ice loads than sites where the winds are light. The conservative simple model results in Table 4 show the possible effect of ice load on elevation in the mountains of Vermont, New Hampshire and southern Maine. In eastern Maine and the northwest corner of Vermont around Lake Champlain, the air temperature was cold enough at low elevations to freeze all the impinging precipitation.

We can compare these rough estimates of the effect of elevation on ice load with a few measured loads. In Enfield, New Hampshire, at 1660 ft, 10 miles southeast of Hanover, we measured ice loads ranging from 0.4 to 0.7 in., less than the 1 in. shown in the table at that elevation. At Gray, Maine, ice loads estimated from photos taken by John Jensenius ranged from 0.7 to 1.0 in., more than the 0.5 in. expected at that eleva-

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tion near the Portland airport, about 15 miles south. Some of the differences between ice loads at low elevations and on hilltops are probably from the higher wind speeds over hilltops as well as from the differences between the actual temperature profile and this assumed gradient.

The range of modeled ice loads shown in Fig. 16 and Table 4 are consistent with ice loads we measured and with most estimated ice loads that we have been able to document. However, as mentioned in Section 6.1.3, we have a number of reports of much larger ice accretions on communication towers on mountaintops in New Hampshire and Maine at elevations between 700 and 1600 ft. The photo in Fig. 22a shows ice accreted on 0.25-in.-diameter guys of a tower on Cadillac Mountain (1500 ft) in Acadia National Park on the coast of Maine. Using the diameter of the guy for scale, assuming a round cross section for the accreted ice, and assuming that this is glaze ice, rather than lower-density rime ice, we estimated an equivalent uniform ice thickness of between 4 and 5 in. This estimate is conservative. If the ice is not glaze ice, or if the accretion cross section is oval, then the equivalent uniform thickness is actually less. It is likely that ice that accreted on structures and trees on some mountaintops was from both freezing rain falling from clouds that were in the warm air layer, and in-cloud icing, from windblown supercooled droplets in low clouds in the cold air layer. The relative contributions to the ice load from the low-level clouds and from the rain can only be estimated because cloud liquid water contents are not measured except at a few sites (at Mount Washington Observatory in supercooled clouds, for example) and by research aircraft. From a database of measurements from research aircraft we have determined the average liquid water content of supercooled stratus-type clouds to be about 0.15 g/m^3

Table 4. Possible effect of elevation on ice load.

Station	Elevation range (ft)	Ice load (in.)
Burlington, VT	340–900	1.1
	900–	1.2
Barre, VT	1160–1720	0.2
	1720–	1.1
Hanover, NH	500–780	0.0
	780–1060	0.8
	1060–1340	0.9
	1340–	1.0
Concord, NH	340–900	0.1
	900–1460	0.5
	1460–	0.6
Portland, ME	100–660	0.5
	660–	0.9
Brunswick, ME	80–630	0.6
	630–	0.7
Augusta, ME	350–	0.8
Bangor	190–	1.2

a. ~5 in. on a 0.25-in. guy on the summit of Cadillac Mountain (photo Robert Parker, U.S. Coast Guard).

Figure 22. Ice accretions with measured or estimated uniform ice thickness.

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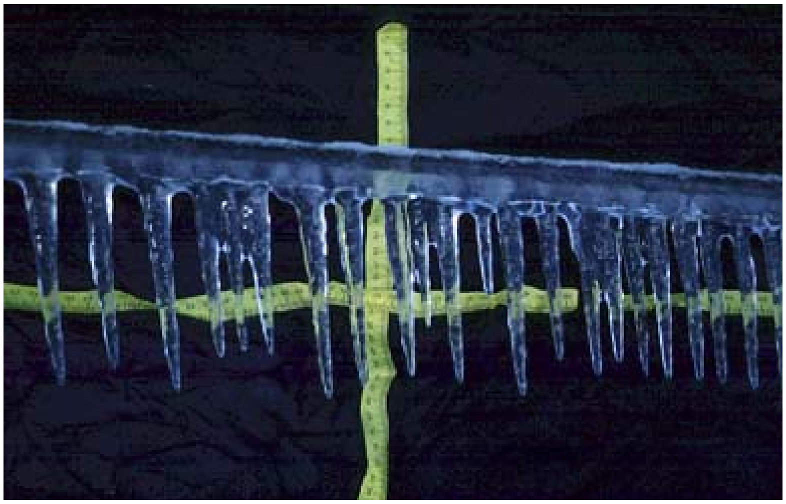
b. 0.2 in. at 100 ft in Swanton, Vermont, at 8:50 a.m. on January 8 (photo Mulherin).

c. 0.7 in. at 110 ft near Rouses Point at 9:20 a.m. on January 8 (photo Jones).

Figure 22 (cont'd). Ice accretions with measured or estimated uniform ice thickness.

(Jones and Ryerson, unpublished). With an average freezing-rain rate of 1 mm/hr in this storm, and an assumed wind speed of 8 m/s at the summit of Cadillac Mountain (about 50% higher than was measured at weather stations, to take topographic effects into account), we estimated a flux of water from the supercooled cloud droplets that is about twice the flux of water from the freezing rain. The mass of ice that accretes on an object from cloud droplets depends not only on the flux of water, but also on the diameter of the droplets and the size of the object. Those factors, along with the wind speed, determine the collision efficiency of the droplets with the structure (Finstad et al. 1988). The accreted ice mass also depends on the density at which the ice accretes, because that determines the size of the accretion, which feeds back into the collision efficiency. The ice density is determined by the cloud liquid water content and air temperature as well as the previously mentioned factors (Jones 1990). The additional flux of water from clouds in the cold-air layer in this storm is likely to have been the major contributor to the accreted ice load on mountaintops that were high enough to be in the low-level clouds throughout the storm and low enough to be below the warm air layer. The contribution to the ice load on trees and structures on the sides of mountains at these elevations would be less pronounced because of the decreased topographic effect on wind speed.



d. 0.7 in. at 1660 ft in Enfield, New Hampshire, on January 12 (photo Mulherin).

e. ~0.6 in. at 1300 ft in New London during the storm (photo Kathy Lowe-Bloch).

Figure 22 (cont'd).

Additional photos of accreted ice and our measured or estimated ice load, in terms of the equivalent uniform ice thickness, are shown in Fig. 22 b through l. Fig. 22b shows a 0.2-in. ice load in Swanton, Vermont, (100 ft) at 8:50 a.m. on January 8. We measured a 0.7-in. ice load (Fig. 22c) near Rouses Point (110 ft) on the Vermont/New York border a half-hour later. The 0.7-in. ice load in Fig. 22d was measured after the storm in Enfield, New Hampshire (1660 ft). The photo in Fig. 22e was taken during the storm in New London (1300 ft). We have estimated an ice load of about 0.6 in. from this photo and the branch diameters, assuming an almost round cross section for the accreted ice. Other ice load estimates from similar photos taken in New London during the storm range up to about 0.8 in. The ice in the photo in Fig. 22f remained on the trees in a road cut near Ossipee (900 ft) three weeks after the storm. The measured load at that time was 0.5 in., providing a lower bound for the load during the storm. We estimated the amount of ice at a site between Vienna and Mount Vernon, Maine (500 ft), on January 8 from the photos in Fig. 22g, calculating a load of 0.2 in. The photo in Fig. 22h of preserved ice on twigs at the same location indicates a load between 0.3 and 0.4 in. Photos taken in Gray near the National Weather Service office (400 ft) are shown in Fig. 22i and j. Estimates from the measured maximum ice thickness and the observed cross-sectional shape (John Jensenius, NWS, personal communica-

f. 0.5 in. remaining at 900 ft in Ossipee three weeks after the storm (photo Jones).

g. ~0.2 in. at 500 ft between Vienna and Mount Vernon, Maine, on January 8 (photo Bill Duffy, Geomantics).

h. ~0.3 or 0.4 in. at the same location, preserved by being buried in the snow after the storm (photo Bill Duffy).

Figure 22 (cont'd). Ice accretions with measured or estimated uniform ice thickness.

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i. ~0.7 in. at 400 ft in Gray, Maine (photo John Jensenius, NWS).

j. ~1 in. at the same location (photo John Jensenius, NWS).

k. ~0.4 in. at 1640 ft near Berlin (photo Wayne Paschal, Berlin Fish Hatchery).

Figure 22 (cont'd)

tion) results in ice loads of 0.7 and 1 in., respectively. Royce Benedict and John Farr at the Berlin Fish Hatchery (1640 ft) in New Hampshire estimated the diameter of the round ice accretion on the fishing lines over the ponds in Fig. 22k to be 3/4 in. Including the icicles in the load and ignoring the small diameter of the fishing line, results in an ice load estimate of about 0.4 in. The photo in Fig. 22l of the ice that accreted on the conductor of the Bangor Hydro transmission line

l. ~0.9 in. accreted on a conductor at about 200 ft east of Deblois, Maine (photo Larry Billings, Bangor Hydro).

m. ~0.7 in. on a twig in Burlington, Vermont (photo Gary Salmon, VD-FPR).

Figure 22 (cont'd). Ice accretions with measured or estimated uniform ice thickness.

that cascaded was taken on January 11 east of Deblois, Maine. Using the scale in the photo we estimated an ice load of 0.9 in. From a video taken at the site, we estimated a 1.1-in. ice load from an accretion that was assumed to have fallen off the static wire. The photo in Fig. 22m of ice on a twig was taken in Burlington, Vermont. Assuming a twig diameter of 0.25 in. (Gary Salmon, personal communication) gives an equivalent uniform ice thickness of about 0.7 in.

6.3 Ice storm history

This severe ice storm is not unprecedented. Summary information on ice storms that have hit the same region affected by the January storm is presented in Table 5. A map of each storm showing the storm footprint and modeled ice loads and concurrent maximum wind speeds at weather stations (for the storms after 1949) is included in Appendix A along with detailed information on the damage caused by these storms, from *Storm Data* (NOAA 1959–present), *Climatological Data* (NOAA 1929 and 1942), journal articles, and newspapers.

7. EXTREME ICE LOADS

Design loads for long return periods and the return periods for extreme loads in severe storms are determined from an extreme value analysis. The peaks-over-threshold method using superstations is described in the next two subsections. Extreme ice loads that we had determined for this region prior to this storm, and new values estimated including our modeled ice loads from

Table 5. Ice storm history in the region hit by the January 5–10, 1998 ice storm.

March 3–6, 1991

NY: devastating ice storm in western and northern NY
VT: power crews kept busy for several days
NH: numerous outages from ice-laden power lines in southern NH
ME: significant freezing rain and sleet storm in central portions

February 14–15, 1986

NH: fiercest ice storm in 30 years over higher elevations in the Monadnock Region in 10-mile-wide swath from MA border to New London

January 8–25, 1979

ME: trees and power lines coated w > 2 in. of ice; heaviest storm in many decades
NH: major disruption to power and transportation

March 2–5, 1976

NY: worst ice storm in memory in western NY: outages lasted longer than 10 days

December 22, 1969–January 17, 1970

MA: severe ice storm
NH: power disruption to many communities
VT: "havoc unbelievable" to forests and utility lines
ME: worst ice storm in many years in southern half

December 4–11, 1964

NY: one of the most devastating freezing-rain storms of record in eastern NY
MA: destruction compared to 1921 and 1942 ice storms

December 29–30, 1942

CT, MA, VT, NH: glaze storm of severe intensity
NY: one of the most severe glaze storms of record, St. Lawrence valley to Albany

December 17–20, 1929

NY: one of worst of record in Buffalo and western NY
NH: unprecedented disruption and damage to telephone, telegraph, and power systems
ME: worst ice storm in half a century; weeks to repair utility lines

this storm, are presented in the following subsection. The return periods of storms like this one are also estimated. The use of regional values, rather than point values, of extreme ice loads is discussed in Section 7.4 for transmission lines. The large horizontal extent of many high-voltage lines makes them more vulnerable to damage from ice and wind storms that hit anywhere along the line route, so they should be designed for heavier ice loads. Systems of communication towers that depend on all towers being operational should also be designed for regional ice and wind loads rather than point loads.

7.1 Peaks-over-threshold method

Researchers often use the epochal method to determine the parameters of an extreme value distribution. They pick the maximum value (of wind speed, snow depth, ice load, etc.) for each year in the period of record, and then use these annual maxima to determine the parameters of a

type I (Gumbel), II (Frechet), or III (reverse Weibull) extreme value distribution. However, for dealing with ice load extremes, the peaks-over-threshold (POT) approach is better for the following reasons:

- At a given location freezing-rain storms occur infrequently and some winters will have no measurable freezing rain. In those years the maximum ice load is zero, which would have to be considered part of the extreme population in the epochal method.
- In other years there will be more than one severe ice storm, each of which may cause larger ice loads than the most severe storms in milder years. The epochal method would not include these severe but not-worst-that-year storms in the estimation of the parameters of the extreme value distribution.
- Because the calendar yea- ends in the middle of the freezing rain season one could argue that it makes more sense to choose maximum ice loads for seasons rather than for calendar years. In a study in which both were tried, the parameters of the extreme value distribution depended on whether the calendar or seasonal year was used (Laflamme 1993).

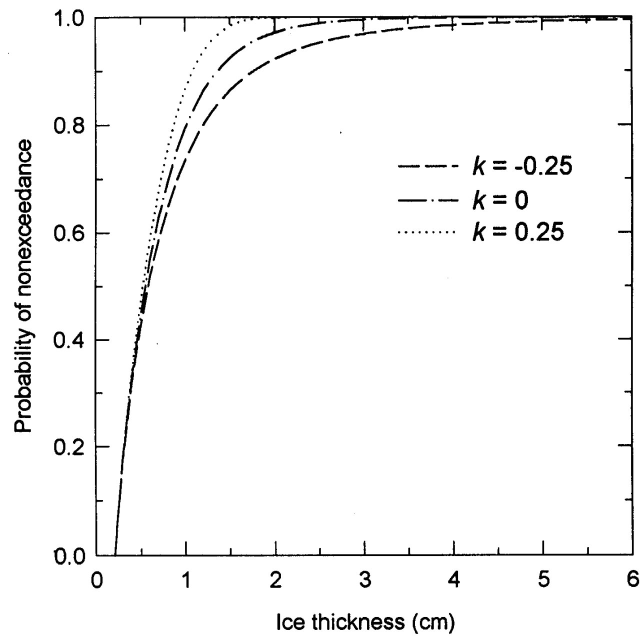


Figure 23. Generalized Pareto distribution.

These problems are avoided using the POT method because loads are chosen as members of the extreme population if they exceed a specified threshold load. The excess of the load over this threshold is used to determine the two parameters of the generalized Pareto distribution (GPD):

$$F(x) = P(X \text{ £ } x\Omega x \geq u) = 1-[1- k(x-u)/\text{a}]^{1/k} \qquad k\ \pi\ 0 \qquad (4)$$
$$= 1 - \exp[-(x- u)/\text{a}] \qquad k = 0.$$

The threshold load is u, the shape parameter is k, and a is the scale parameter. The cases $k = 0$, $k < 0$, and $k > 0$ correspond to the extreme value distribution types I (shortest infinite tail), II (infinite tail length), and III (finite tail length, $x < \text{a}/k$) shown in Fig. 23. Typically k ranges between –0.5 and 0.5. If the data are correctly described by a GPD, then k is not dependent on the load chosen as the threshold, as long as the threshold is chosen high enough.

Probability weighted moments (Abild et al. 1992, Wang 1991, Hoskings and Wallis 1987) are often used to determine the distribution parameters k and a. This method is particularly efficient for distributions with $k < 0$, which seems to be generally true of extreme ice load data. Estimates of the GPD parameters are provided by

$$k = \frac{4b_1 - 3b_0 + u}{b_0 - 2b_1} \quad k = \frac{4b_1 - 3b_0 + u}{b_0 - 2b_1}$$
$$a = (b_0 - u)(1+k) \quad a = (b_0 - u)(1+k)$$

where (5)

$$b_o = \frac{1}{l}\sum_{i=1}^{l} x_{(i)}$$

$$b_1 = \frac{1}{l}\sum_{i=1}^{l} \frac{i-1}{l-1} x_{(i)}$$

(Wang 1991), where the $x_{(i)}$ are the ordered sample, $x_{(1)}$ £ $x_{(2)}$ £ ... £ $x_{(l)}$ of loads greater than the threshold load *u*.

A variety of methods can be used to define the threshold load *u*. It should be high enough that only true extremes are used to estimate the parameters of the GPD, but low enough that there are sufficient data so sampling error is not a problem. Simiu and Heckert (1995) showed the variation in *k* with *u* for fastest-mile wind speed data. Some authors specify the threshold as a percentile of the number of cases. For example, Walshaw (1994) used a threshold at about the 95th percentile of his 10 years of hourly maximum wind gusts. Sometimes the threshold is determined on a physical basis (Abild et al. 1992).

Once the parameters of the distribution have been determined, the load x_T corresponding to a specified return period *T* is calculated from

$$x_T = u + \mathrm{a}\,[1 - (\mathrm{l}T)^{-k}]/k, \qquad (6)$$

where l is the occurrence rate (number per year) of storms exceeding the threshold load.

7.2 Superstations

The superstation concept is presented in Peterka (1992) for extreme wind speeds. The 50-year return-period wind map in ASCE 7-88 showed small regions in the Midwest with high winds. Peterka argued that these small-scale variations in the extreme wind speed were not real, but were due to sampling error from determining the parameters of the extreme value distribution from relatively short data records. He suggested that the records of extreme winds from different weather stations with the same wind climate could be appended to each other to form a superstation with a much longer period of record. This long period of record supplies many more extremes to use in the extreme value analysis and thus produces better estimates of the parameters of the extreme value distribution. For example, Peterka created a wind superstation that included 29 stations in 11 states and had a 924-year period of record. The limitation on forming the superstation was that the maximum annual winds from the different stations in the superstation should be uncorrelated. If they are not, if the maximum annual wind speed in Cleveland, for example, typically occurred in the same storm as the annual maximum in Cincinnati, then including the second station supplies no new information on the extreme wind climate.

In forming the superstations for ice loads in this region we took into account the number of severe ice storms at each station, the number of times adjacent stations were in the same severe storm, the frequency of ice storms at each station, station elevation, latitude, proximity to water, and relief. We attempted to balance grouping only stations likely to have the same icing climatology against the desire to create superstations with as long periods of record as possible to reduce sampling error. The weather stations used in the extreme value analysis were required to have complete historical records of hourly weather data, including present weather, as well as either hourly or 6-hourly precipitation amounts. Thus, we could not include data from CRREL (no

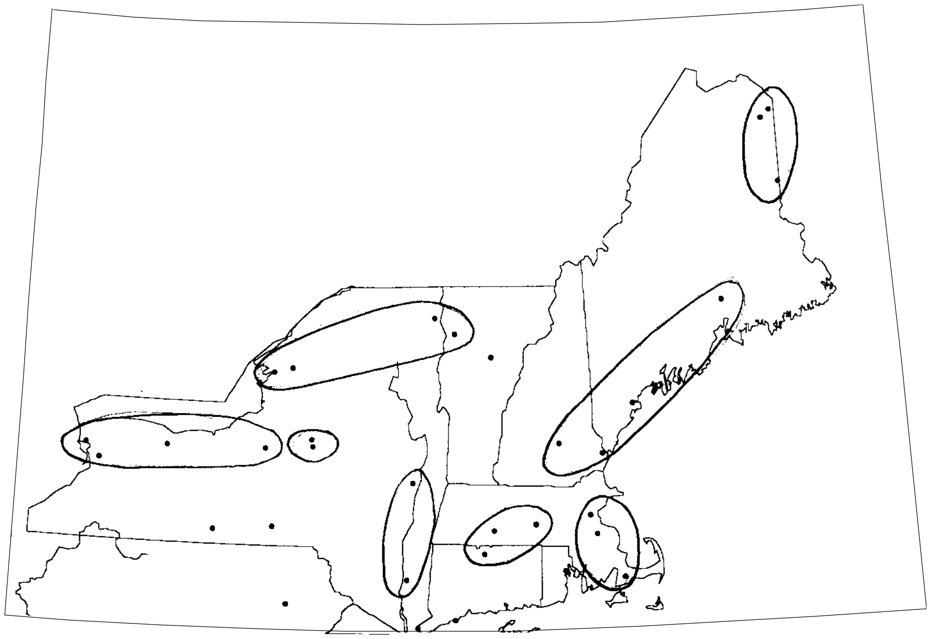


Figure 24. Freezing rain superstations in the Northeast.

present weather), Mount Washington Observatory (3-hourly weather data for most of the period of record), Massena, Brunswick, or Augusta (significant gaps in precipitation data). Ultimately, we defined the superstations shown in Fig. 24. While Barre was not included in a superstation, it was ultimately grouped with other stations in a large amorphous region. The number of extreme ice storms at these superstations is considerably less than the thousand that Peterka considers ideal; however, sampling error is significantly reduced in the superstations compared to the individual stations.

7.3 Extreme ice loads

7.3.1 Ice loads for a 50-year return period

A load that has a 2% chance of exceedance in any year is called a 50-year return-period load. A 50-year return-period load does not recur every fifty years. It may happen two years in a row, twice in 30 years, or only once in a particular 100-year period. There is a 64% probability that a 50-year load will be exceeded in any 50-year period and 39% and 15% probabilities that 100-year and 300-year return-period loads, respectively, will be exceeded in 50 years (Table 6).

In the extreme value analysis, we found the 75th-percentile ice load to be a good threshold for extreme ice loads for this region. It results in threshold uniform ice

Table 6. Probability of exceeding the load for a given return period at least once.

$$p_N = 1 - (1 - p_1)^N$$

	Return period for load		
Lifetime (years)	50 years	100 years	300 years
1	.02	.01	.003
2	.04	.02	.01
5	.10	.05	.02
10	.18	.10	.03
20	.33	.18	.06
40	.55	.33	.13
50	.64	.39	.15
100	.87	.63	.28
300	1.00	.95	.63

thicknesses varying around 0.1 in. and occurrence rates for extreme storms of between one and two per year. The results of the extreme value analysis for the superstations, based on the simple model results using the weather data for this storm and historical weather data, are summarized in Table 7. The table lists the number of years in the period of record for each superstation and the 50-year return-period ice loads, followed in parentheses by the 50-year loads that were calculated prior to this storm. The updated 50-year return-period loads in Table 7 were used to revise the ice-load map currently in draft form for the 1998 edition of ASCE 7 *Minimum Design Loads for Buildings and Other Structures*. That revised map is shown in Fig. 25.

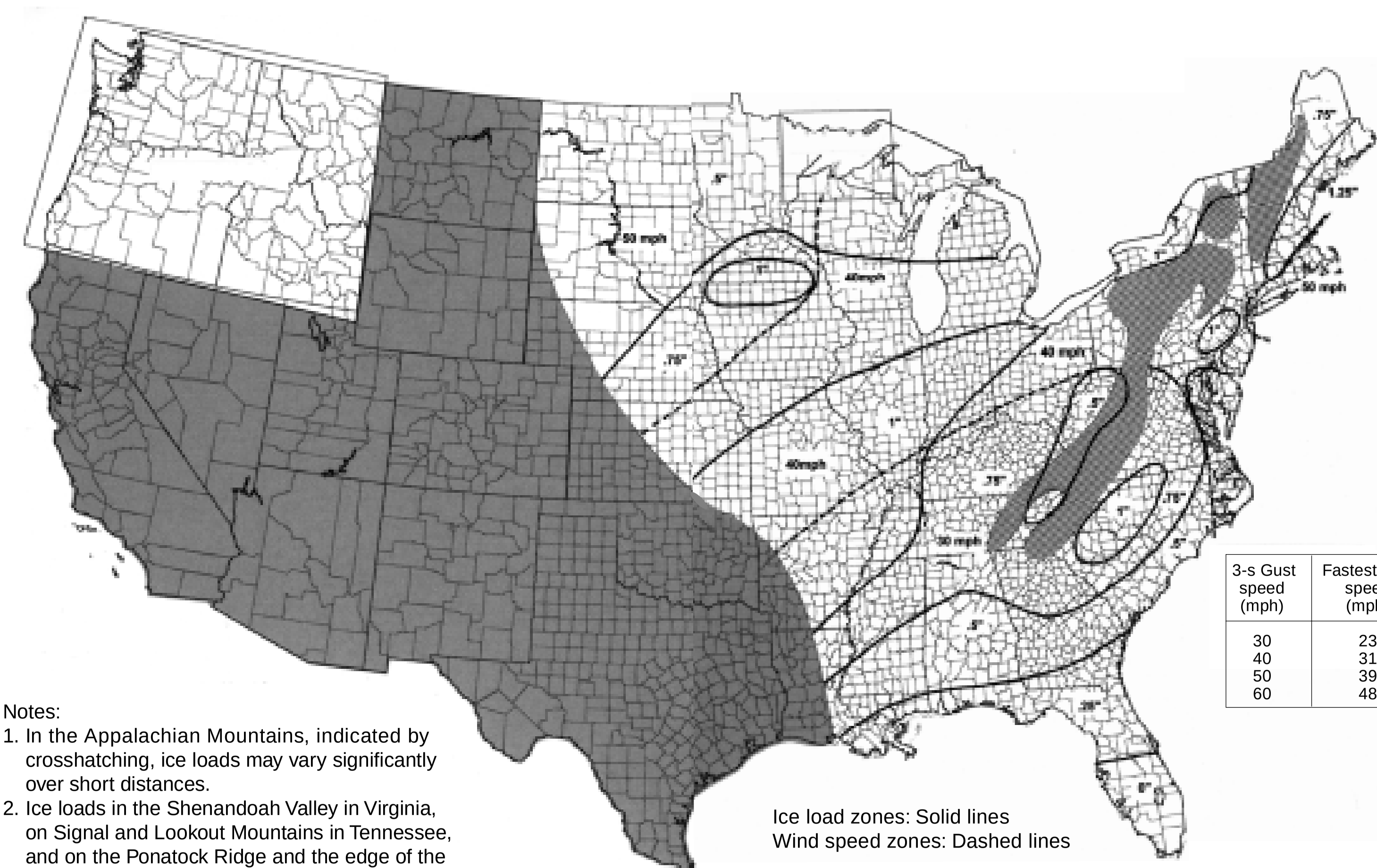
Table 7. Results of extreme value analysis.

Superstation	Period of record (years)	50-yr return period ice load (in.)
Watertown Fort Drum Plattsburgh AFB Burlington	94	0.9 (0.6)
Barre	21	0.6 (0.6)
Concord Pease AFB Portland Bangor	136	1.1 (1.0)

Note that Barre is the only weather station with hourly data at a high elevation in either Vermont or New Hampshire. However, it cannot represent the wide variety of conditions that occur over higher terrain in that region. Furthermore, because of the short period of record of the weather data at Barre, determining extreme ice loads for even relatively short return periods is very uncertain. In using the data at Barre, we are not only extrapolating 50-year loads from only 20 years of data, we are also doing that extrapolation from the recent past (since 1972) in which the weather in the United States was mild, with relatively few storms of any sort. If we could use the data recorded at coop weather stations, many of which have records dating back to 1948, we could substantially increase our understanding of the severity and geographical distribution of ice accretion from freezing rain in this difficult region. An empirical approach developed by Dr. Charles Konrad at the University of North Carolina (in review) identifies days with freezing rain from the daily precipitation and snowfall records and the daily maximum and minimum temperatures. We could apply our ice-load models to data from those freezing-rain days to get estimates of ice loads. However, these load estimates would not include the additional ice that may accrete at elevations high enough to be in low clouds that may form in the cold air layer during freezing-rain storms. As was indicated for this storm, ice accreted from supercooled clouds may be significant on structures built on mountaintops. To model the accretion of ice from supercooled clouds, we would use the cloud layer data from the hourly weather stations, estimates of cloud liquid water contents and drop sizes, and upper air wind and temperature data at the stations where upper air data is obtained. In-cloud icing at all times, not just during freezing-rain storms, is probably the dominant ice-loading mechanism on very tall towers (1000 to 2000 ft tall) and any structures on mountaintops.

7.3.2 Return period for severe ice storms

The January ice storm was the worst ever in the experience of many people in upstate New York and northern New England, both in the amount of ice that accreted on trees and structures, and the extent of the storm. Using the parameters of the GPDs, we can estimate return periods for the ice loads in this storm. In Table 8 are shown the return periods for ice loads ranging from



3-s Gust speed (mph)	Fastest-mile speed (mph)
30	23
40	31
50	39
60	48

Ice load zones: Solid lines
Wind speed zones: Dashed lines

Notes:
1. In the Appalachian Mountains, indicated by crosshatching, ice loads may vary significantly over short distances.
2. Ice loads in the Shenandoah Valley in Virginia, on Signal and Lookout Mountains in Tennessee, and on the Ponatock Ridge and the edge of the Yazoo Basin in Mississippi may be higher than the mapped loads.
3. In the shaded region icing studies are incomplete. Consult other sources of information to determine design ice loads and wind speeds (see text). In areas where freezing rain is known to occur, a minimum uniform ice thickness of 0.5 in. with a 50-mph 3-s gust wind speed should be considered.

Figure 25. Fifty-year return-period uniform ice thicknesses due to freezing rain with concurrent 3-s gust wind speeds: contiguous 48 states.

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Table 8. Return periods for large ice loads.

Uniform ice thickness (in.)	Upstate New York and NW Vermont	Coastal and Central Maine and New Hampshire
0.5	15	5
0.75	35	20
1.0	65	40
1.25	100	85
1.5	145	160

0.5 in. to 1.5 in. for the two superstations in upstate New York and northwestern Vermont and in coastal and central Maine and New Hampshire. The larger equivalent uniform ice thicknesses from this storm ranged from 0.75 to 1.25 in., which corresponds to return periods ranging from 35 to 100 years in the NewYork–Vermont superstation and 20 to 85 years in the New Hampshire–Maine superstation. These return periods are consistent with the information from *Storm Data* and other sources in Appendix A on severe ice storms in the same area earlier in the century. Extensive tree damage and associated damage to the electrical distribution system can be expected with only 0.5 in. ice loads, which have a return period of between 5 and 15 years. Because of the sparse weather data and the rough terrain in interior New Hampshire and most of Vermont we have not estimated the return period for a storm like this in that region. The ice loads in the January storm varied from none to a lot over very short distances, associated with changes in elevation, exposure, and the local temperature profile.

7.4 Regional loads

The concept of regional loads, rather than point loads, applies to both wind loads and ice loads for the design of transmission lines. The ice load map in ASCE 7 shows 50-year return-period loads at a point. It is used in the design of communication towers and power lines. However, power line systems have large horizontal extents compared to communication towers. So the risk of exceeding the 50-year return-period point loads anywhere in the system is higher than the risk of exceeding that load at a particular point. For example, in Essex Junction there is a 64% probability that the ice load will exceed the 50-year return-period ice load on the ASCE 7 map at least once in any 50-year period (Table 6). However, a transmission line that extends from Essex Junction to White River Junction encounters ice storms that occur anywhere between the two cities. Thus, designing a transmission line, which extends tens or hundreds of miles, and a single TV tower for the same ice load results in a greater risk of failure for the transmission line than for the tower. The risk of exceeding the 50-year return-period point ice load increases with the horizontal extent of the transmission line.

8. CONCLUSIONS

The January ice storm in New England and upstate New York was notable for both the large area it covered and the amount of ice that accreted on trees and structures. Both of these factors, along with the rural character of the region, contributed to the long power outages during and following the storm. In some areas in the United States customers were without power for three weeks and in Canada outages lasted even longer. This storm, however, is not without precedent. The ice storm in December of 1929, in particular, appears to cover almost the same region with ice loads comparable to those in this storm. This is consistent with return period estimated by our extreme value analysis of between 35 and 85 years for storms of this magnitude in the Northeast. Other storms have produced ice loads comparable to those in this storm, but over a smaller region.

For the most part, structures that were designed for heavy ice withstood the loads imposed by

this storm. There was little damage to high-voltage transmission lines and communication towers in northern New England. However, lower-voltage transmission lines in narrow right-of-ways, distribution lines, and service drops vulnerable to damage from broken branches and trees took a beating. As has long been recognized, the level of damage to these structures from trees could be reduced by expert and frequent tree trimming and the removal of danger trees adjacent to the right-of ways.

Severe ice storms are not confined to this part of the country. A widespread ice storm in the Southeast in February 1994 caused month-long power outages in Mississippi and brought down more than 16 communication towers. Back-to-back storms in Iowa in 1990 and 1991, the second followed by cold temperatures and high winds, caused cascade failures of hundreds of miles of transmission lines. Although some utilities design their major transmission lines for a heavy ice load, they are required to design only for the loads specified by NESC. The completion of the ice load and concurrent wind speed map proposed for ASCE 7-98 would provide 50-year return-period loads from freezing rain for the entire country to use in the design of ice-sensitive structures.

When ice-sensitive structures, including communication towers and power transmission lines, fail in an ice storm, it is often assumed that the ice load on the structure was greater than the load it was designed for. The obvious simplistic solution is then to design for a larger ice load. However, the collapse may have been initiated by a single component failing, perhaps because of previous damage or deterioration. When that component fails, the transfer of the load it was carrying, including the ice load and the wind load on the ice-covered structure, may overload other parts of the structure, which then may fail under a load they were not designed for. Attributing this kind of failure to the ice load, and then concluding that it is necessary to design for more ice, does not address the real problem. For tower and transmission line engineers to better design structures to withstand the loads imposed by these severe storms, they must not only determine how much ice accreted on structures in a damaging ice storm, they must also determine what initiated the failure in the structures that collapsed.

9. ACKNOWLEDGMENTS

We obtained information on the ice storm and ice-storm damage to trees and the power and communications infrastructure from conversations with many people across all three states in the Region 1 disaster declaration, as well as in New York and Canada. We thank David Duplissis (CellularOne); David Klumb and Dusty Kelley (United States Cellular); Bob Picard (Atlantic Cellular); Mark Osborne (WBFB-FM); George Crouse (Northern Communications); Scott Fybush (North East Radio Watch); John Erichsen (PiRod); Verle Miller (Rohn); Bill Uphoff (World Tower Co.); Robert Parker and Derek Chase (U.S. Coast Guard); Stan Manning and Andy Armstrong (WKZS-FM); Martha Dudman (WEZQ-FM); Russ Dumont (WCDQ-FM); James Corbin (WWNY-TV); Don Darling (Maine Department of Environmental Protection); staff at the Mount Washington Observatory; Bill Duffy (Geomantics); David Plante, Reggie Lang, Teri Beaulieu, Kevin Cote, Douglas McDonald, and Karen Mackey (Public Service of New Hampshire); Betty O'Neil, Tom McDermott, Stephen Jeffery, John Knott, and Bud Upmal (FEMA); Tom Bragg (Central Maine Power); Larry Billings, Ken Miller, Dean Dennis, Jeff Fenn, and George Baker (Bangor Hydro); John Jensenius and Steve Hogan (National Weather Service); Art DeGaetano (Northeastern Regional Climate Center); MSgt. Shook and TSgt. Burke (Air Force Combat Climatology Center); John Farr, Royce Benedict, and Wayne Paschal (Berlin Fish Hatchery); Jack Crowther and Doug Best (Central Vermont Public Service); Richard Holmes (Granite State Elec-

tric); Charles McAlpin (Eastern Maine Electric Coop); Sharon Yeaton and Henry Lynch (New Hampshire Electric Coop); Steve Guyette (Citizens Utilities); Dick Simays (Vermont Electric Coop); Jeff Bell (Bell Atlantic); Ron Moliere (Isaacson Steel); Ray Letourneau (Exeter and Hampton Electric); Eric Werner (Concord Electric); Scott Ryder (New England Power Service Company); Dottie Schnure (Green Mountain Power); Alan Peabody (Dryden and LaRue); Donald Marshall (LeBlanc and Royle Telcom, Inc.); Tom Dunn (Vermont PSD); Jim Thyng (New Hampshire PUC); Samy Krishnasamy (SAMTECH); Donna Alvarez, Russ Hobby, Brian White, Kathy Lowe-Bloch, Patrick Coyne, and John Monk (Whitten's 2-way Service); Roger Holst (PCT Communications); Tami Bill and Matthew Tilley (Radio Telephone of Maine); Mark Osborne and Rick Hunnewell (Brownie's Communication); Bill Kostis (Southern Maine Communications); Jerry Ouellette (Atlantic Communications); Sonny Lepage, Richard Ward, and Dave Struble (Maine Forest Service); Jennifer Boffinger, Phil Bryce, and Kyle Lombard (New Hampshire Department of Resources and Economic Development); Brent Teillon, Laura Cadmus, Barbara Burns, and Gary Salmon (Vermont Department of Forests, Parks, and Recreation); Bob Burt (Green Mountain National Forest); Kevin Peterson (Appalachian Trail Conference); Gail Michaels and Bill Framen (U.S. Forest Service Northeast Area GIS Group); Wayne Millen (White Mountain National Forest); Rick Heinis (Lakes Region Mutual Fire Aid Association); and Mark Twickler, Eric Meyerson, and Barry Keim (University of New Hampshire).

As CRREL is located in the middle of the region that was hit by the ice storm, CRREL personnel and their friends and relations provided additional storm information both from their personal experiences and additional investigations they had undertaken from their professional interest in cold regions problems. We also had general discussions on freezing rain with a number of researchers at CRREL. We thank Jamie DiFillippe, Jean Frankenstein, Marianne Walsh, Duane Eppler, Cynthia Whitney, Kevin Carey, Bert Davis, Andrew Tuthill, Susan Hardy, Rachel Jordan, Mary Albert, Kate White, Mike McLane, Susan Taylor, Charles Racine, Jim Martel, Steve Flanders, Karen Henry, Bert Yankielun, Mark Hardenberg, Deb Meese, Larry Gatto, Gary Koh, Susan Koh, Lynne Hunter, Tom Tantillo, Dave Fisk, Dave Cole, Richard Detsch, Sharon Borland, George Blaisdell, Alan Greatorex, Nick Collins, Jeff Koenig, Charles Ryerson, Kerry Claffey, Randy Hill, Terry Tucker, Alan Ricard, Don Perovich, and Roy Bates.

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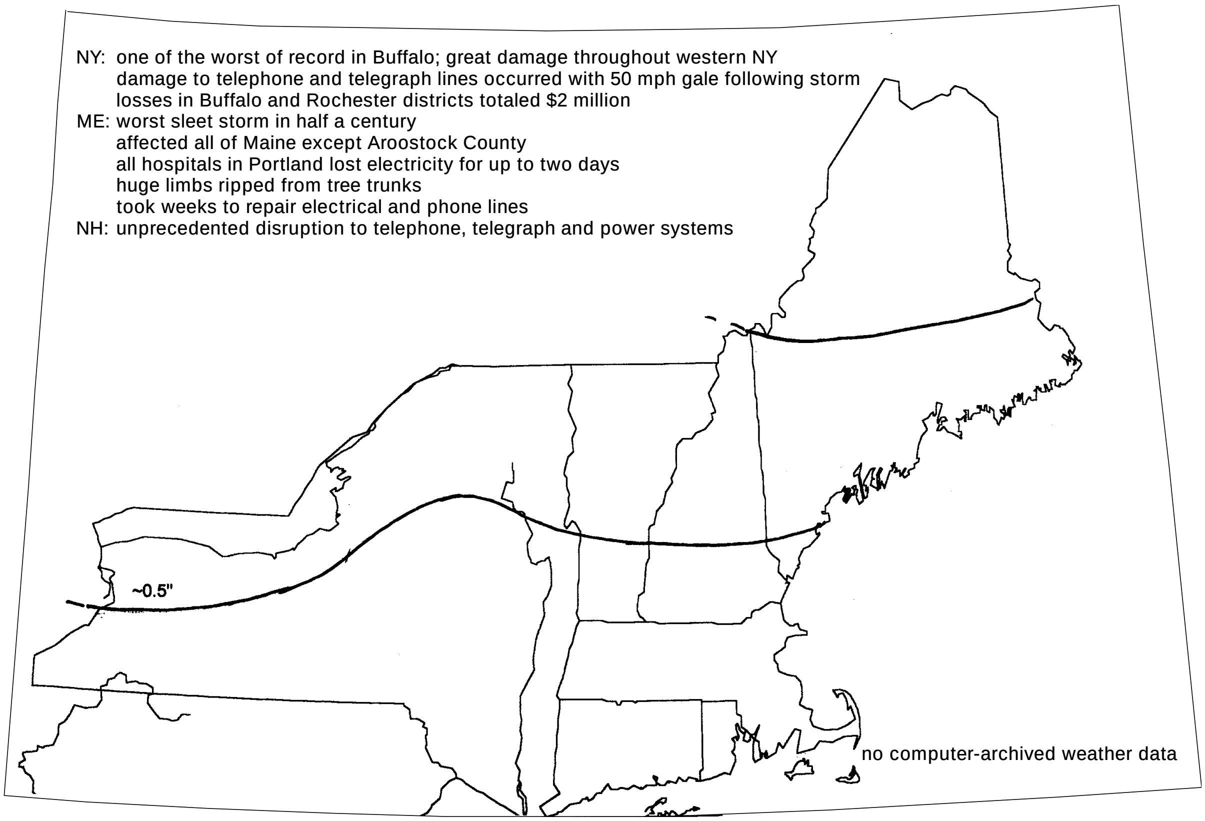
APPENDIX A. HISTORICAL ICE STORMS IN NORTHERN NEW ENGLAND AND NEW YORK

December 17–20, 1929



MAINE

Bangor Daily News:

Beginning on the 18th, an ice storm and then a 4- to 10-in. snowfall hit southern Maine, including Bangor, Waterville, Lewiston, and Portland. Bangor suffered an all-day sleet storm and snow amounting 6 in. Line breaks and short circuits, caused by the weight of ice on wires and falling tree limbs, resulted in loss of telephone and electrical service for some time. Wires came down as fast as they could be put back up. All rail service down for several days due to broken telegraph lines.

Kennebec Journal (Augusta):

The "worst sleet storm that southern, central, and eastern Maine have experienced for years… worst sleet storm since 1921" caused thousands of dollars damage to wire communications. Although only 4 in. of snow and a brief ice storm that did not disrupt traffic or communications occurred in Augusta, fruit and shade trees in York County suffered extensive damage from broken limbs. Portland's parks appeared "shell-blasted… with large limbs and whole trees broken and cracked apart." The main transmission line from the West Buxton hydro station was out of service for two hours. Rain atop a 10- to 12-in. snowfall made driving dangerous in Waterville. In Lewiston, sleet and rain followed 6 in. of damp snow. WCSH's broadcast tower in Portland fell

due to icing from the 1.73 in. of rain that fell. Hardest hit were coastal areas between Yarmouth and Castine. Brunswick sustained greater damage to its wire services than any other place. Northern Aroostook County had only a 10-in. snowfall without experiencing much disruption.

NEW HAMPSHIRE

Concord Daily Monitor:

"One of the most severe storms to hit New England for several years…did untold damage for several days." Rain turning to ice as it fell caused "unprecedented disruption and damage" to telephone, telegraph, and power systems for most of central and northern New Hampshire and seriously hampered transportation and highway traffic. Tree damage in Concord, especially to the evergreens, was severe. The Concord Electric Co. sent crews out to remove fallen limbs from its wires, although wire damage in the city was slight and service was uninterrupted. The damage was worse starting just north of the city. Officials felt that it would take the smaller utility companies up north weeks and possibly months to fully recover. The power was completely cut off in the towns of Ashland, Plymouth, Bristol, and Hill, and partially in Laconia and Franklin. Telephone and telegraph lines and poles were down for "hundreds of yards" in places. In Canaan, power was out for two days and the roads were impassable due to downed trees and lines. Public Service of New Hampshire sent line crews to the hard-hit areas of Tilton and Laconia. Five hundred linemen were replacing more than 1000 poles in Maine and damage was estimated at many hundreds of thousands of dollars. Montreal was reportedly completely cut off from the outside world, except by radio, with damage expected in the "many thousands of dollars" range. In the northern part of the state, railroad officials reported conditions without parallel to their knowledge. Trees with branches covered by more than three tons of ice were littered across their tracks.

The Manchester Union:

Central New Hampshire struck by a rain- and ice storm called the "worst storm in years." The area affected extended from Franklin to Franconia Notch and included Grafton, Carroll, Belknap, Strafford, and Rockingham counties. It was centered in central and eastern New Hampshire but whole state south of the White Mountains was affected, while Cheshire county and the western side of the state as far north as Claremont was spared. The three-day storm caused several hundred thousand dollars in damage from the White Mountains to the Massachusetts border. Forty-five poles were down near Sunapee and Georges Mills, 100 poles down between Laconia and Meredith, trees were bent "almost to the ground" from the weight of ice, power outages caused mainly by trees on the lines. Veteran residents had never witnessed a storm like the duration of this one, saying that these storms are usually over in 24 hrs. Untold damage to the forests everywhere, millions of pine trees ruined, great danger to people from the crashing trees and limbs.

The Landmark (Lebanon, NH):

No storm-related articles found.

VERMONT

Burlington Free Press:

Snow, sleet, and rain froze on contact forming a 1-in.-thick casing around electric wires in Rochester, New Hampshire. Heavy limb damage sustained by orchards. Freezing rain followed a 4-in. snowstorm there. Streets were glazed in Montpelier causing "many minor motor accidents."

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Rutland Daily Herald:

No storm-related articles found.

NEW YORK

The December 17–18, 1929 ice storm was described in a short paper in *Monthly Weather Review* by J.H. Spencer (1929). The ice storm was one of the worst of record in Buffalo. There was great damage to trees as thousands of large branches were broken by the weight of the ice. A drawing of ice on a forsythia branch shows about a 0.5-in. uniform radial ice thickness. The ice storm was followed by cold weather. A 50-mph gale on December 20th and 6 in. of snow on the 21st caused additional severe damage and hardship throughout western New York. Hundreds of linesman were brought in to repair damaged power, telephone and telegraph lines. Eight thousand poles and 15,000 miles of wire were pulled down by the ice and high winds.

The New York Times:

In eastern and northern New York, back-to-back freezing-rain storms snapped miles of wires beneath the weight of ice. Glens Falls hardest hit with 1000 lines down. Attica was isolated and without power for at least 24 hrs. Saratoga Springs "less buried in ice." Buffalo hit by a 2-day ice storm. Communications broken from Plattsburgh to Buffalo (tree debris piled up faster than it could be removed). New Hampshire and Maine "hardest hit" with slightly less serious conditions in Vermont and Massachusetts. Worst "sleet storm" in Portland, Maine's history.

Plattsburgh Daily Press:

(Articles nearly identical to those found in the NY Times, with some minor additions.) Eastern New York was between "order and chaos" following two rain storms and "heavy frosts" and workers worked desperately to restore electricity and communication, repairing "broken wires and ice-snapped poles." In Saratoga Springs, Ballston Spa, and Schenectady, workmen cleared thousands of fallen trees and limbs. Ninety-one of 120 telephone circuits were out in Glens Falls, 53 of 102 in Saratoga Springs, and 31 of 303 in Albany.

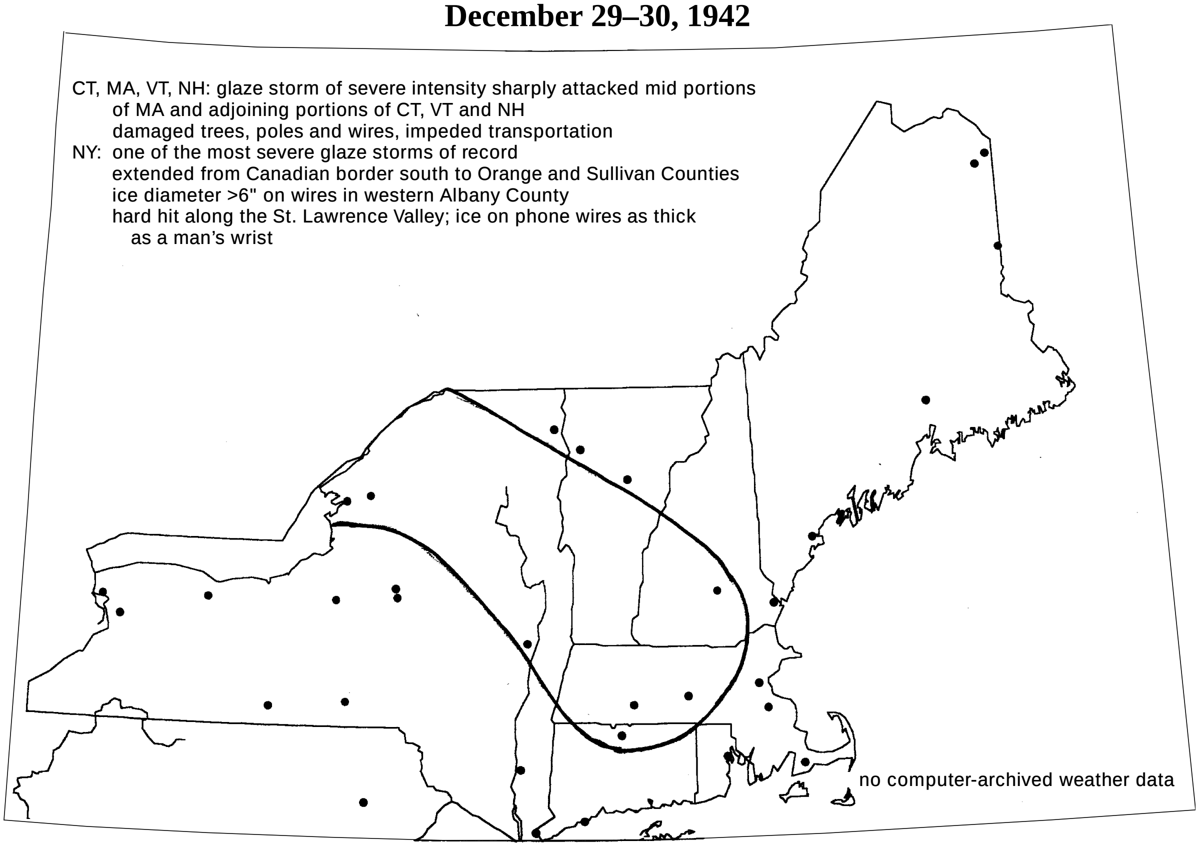
Albany Times-Union:

"Unprecedented havoc wreaked by three days of rain and sleet. Worst sleet storm ever experienced isolated all eastern Adirondack towns. A score of towns in northern and northeastern New York cut off from communication and power. More than 5,000 square miles of Vermont and New York affected. About 30 towns were listed as isolated. Though not as bad in Albany where the preliminary damage estimate was $1.5 million, falling poles, trees, and branches blocked roads out of the city to the north. From Mechanicville to the Canadian border everything came to a virtual standstill. Glens Falls/Saratoga Springs area hardest hit, where more than 350 poles were downed. Telephone lines sustained considerable damage. Linemen were brought in from Albany, Poughkeepsie, Schenectady, Syracuse, and Kingston. A 94-year-old resident who had lived in Saratoga Springs for 80 years said storm was the most destructive he had ever seen. Other old-timers likened the destruction to that of the Blizzard of 1890. Fort Edward completely without power while Hudson Falls was nearly so. Trees in Buffalo's parks were destroyed by the ice-load.

Syracuse Herald:

Cold rain froze on contact with the city's streets causing widespread disruption of transportation. Officials estimated more than 200 breaks in the telephone lines between Fulton and Oswego, no available service out of Watertown, and gangs of linemen working near Mannsville and Pulaski. In addition to towns previously mentioned, Schuylerville and Greenwich were completely isolated. Orchards were severely damaged and transportation crippled by glaze in western Ontario. The worst damage was experienced in London where hundreds of miles of poles and lines were toppled and the damage was estimated to be in the neighborhood of $250,000. The Niagara area also suffered severe orchard damage.

December 29–30, 1942



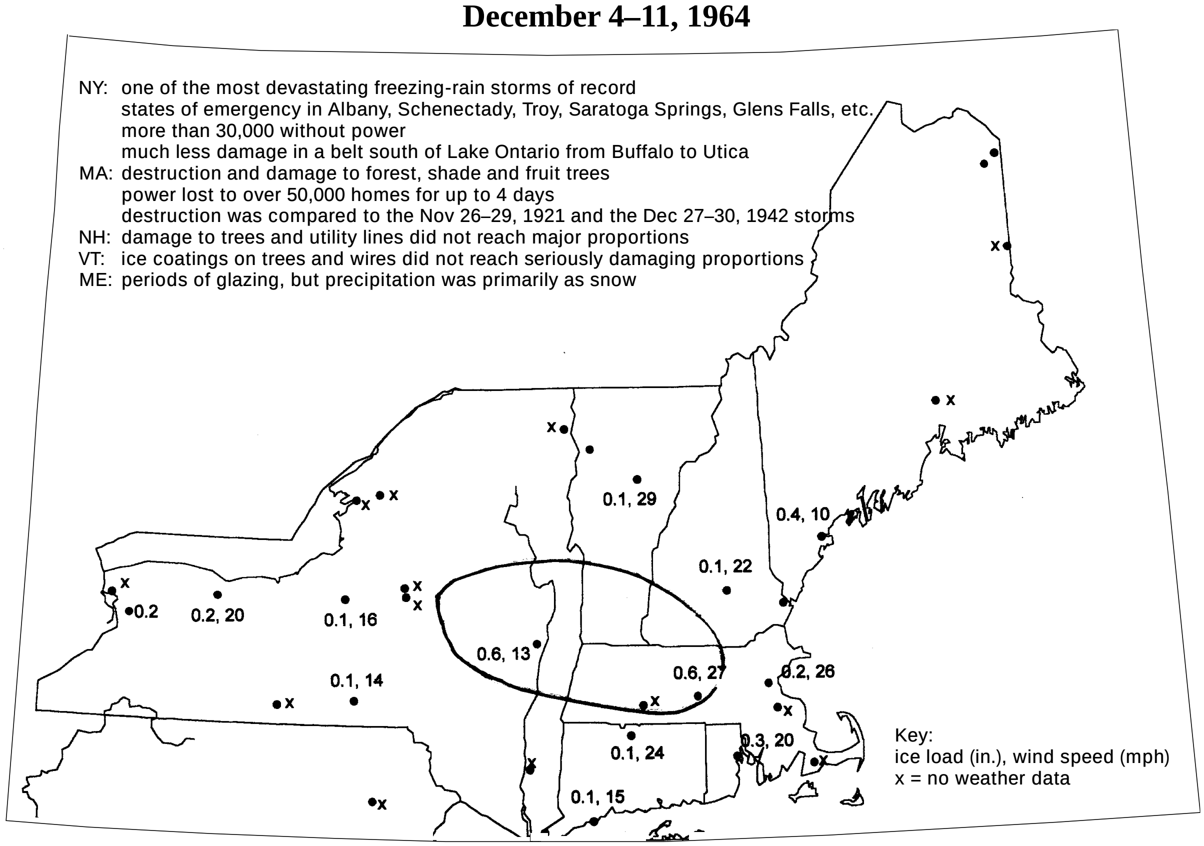
(summary from *Climatological Data* 1942)

On the 27th of December, continuing through the 30th, one of the most severe ice storms of record moved into the eastern half of New York. Severe icing occurred in the area from the Canadian border south to Orange and Sullivan counties. South of the Adirondack Mountains the glaze was severe only at elevations over 900 ft. Albany itself was not affected by the storm, but in the higher elevations in the western portions of Albany County, ice accretions on overhead wires were more than 6 in. in diameter. Along the St. Lawrence Valley the coating of ice on telephone wires was reported to be as thick as a man's wrist. Between 500 and 1000 telephone poles were down in the center of the storm region, 9600 houses were without power, and in Ogdens-

burg water was rationed because of a lack of power. Communication to many villages was severed. The damage to sugar maples, fruit orchards, and ornamental trees was severe.

The mid-portions of Massachusetts and neighboring portions of Connecticut, Vermont, and New Hampshire were hit by a glaze storm of severe intensity on December 30th that caused damage to trees, poles, and wires.

December 4–11, 1964



Storm Data

12/3–6/64

MAINE Southern [ME13,14] IC2 (Glaze, sleet, and snow)—Periods of glazing from freezing rain or drizzle occurred on the 4th and 5th, with periods of sleet on the same dates. Glazing was most extensive in extreme southwestern Maine. Precipitation was primarily as snow, with storm totals mostly from 10 to 18 in. during the four-day period. Less snow, mostly 4 to 10 in., and little or no glaze, fell over northern Maine.

12/3–6/64

MASSACHUSETTS State [MA01,02,04>09] (Glaze)—Icing from freezing rain and drizzle, sometimes with sleet, began in some areas on the 3rd and over nearly all the state by the 4th. Only Cape Cod, where temperatures remained above freezing, escaped. The ice storm continued through the 5th and in some areas into the 6th before changing to snow. Worst affected was a belt from the northeastern to southwestern corners of the state. Ice built up to 0.5 in. thick on limbs, wires, and other exposed surfaces over much of this belt. In some areas the ice became 1.0 in. in

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thickness. Traffic was severely hampered as even sanded roads soon were recoated with ice. Many roads were closed to traffic. The greatest effect was the destruction and damage to forest, shade, and fruit trees as branches or whole trees broke under the weight of ice. Falling trees and branches blocked streets, crushed many cars, and damaged homes. But the most devastating effect was their falling onto power and phone lines. Power was lost to well over 50,000 homes. Some whole towns lost power. Some homes remained without heat or light for four days or more. Residents took refuge in public emergency shelters set up in schools, etc., or with relatives and friends elsewhere. The extent of tree damage was remarkable especially as the storm was not accompanied by strong winds. Some tree experts stated that the 1964 drought may have weakened the trees. Trees experts and power company officials stated that the destruction was the worst in some areas since the extremely severe glazing of November 26–29, 1921, which in some areas had coated wires by ice up to 2 in. in diameter. At other places the storm was comparable to the severe glaze storm of December 27–30, 1942. Though no direct storm death or injury was reported, numerous injuries resulted from falls on extremely slippery streets and walks and from auto skidding accidents. Several deaths also resulted from auto accidents during the storm and one man died while clearing his sidewalk.

12/3–6/64
NEW HAMPSHIRE Central and southern portions [NH03>07] IC3 (Glaze, sleet, snow)—Periods of freezing rain or drizzle, sleet, and/or snow occurred on December 3–5, changing to all snow on the 6th. Glazing was most serious in the southern portion where roads quickly iced over again after being sanded. Foot and vehicular travel became very hazardous. Damage to trees and utility lines from heavy ice loading did not reach major proportions. Total snowfall ranged mostly from 8 to 12 in.. In northern New Hampshire, snowfall totals were generally somewhat less.

12/3–6/64
VERMONT State [VT01>05] IC3 (Glaze, sleet, snow)—Periods of freezing rain or drizzle and of sleet occurred mainly on the 4th and 5th but in a few areas in southern portion on the 3rd and at a few stations on the 6th. Glazing caused very hazardous roads and walks, with many minor accidents resulting. Ice coatings on trees and wires did not reach seriously damaging proportions. Precipitation was mostly as snow. Snowfall totals ranged mostly from 6 to 12 in.

12/4–5/64
NEW YORK East Central [NY12,19,20] (Freezing rain)—One of the most devastating freezing-rain storms of record. Storm damage concentrated in eastern Mohawk and upper Hudson Valleys from Canajoharie east to New England border and Albany north to Glens Falls area. Rain totaling from 0.8 to 1.5 in. fell over most of two-day period and froze on objects to a thickness of more than one in. while temperatures ranged between 26 to 31 degrees. Trees, limbs, and power lines were downed in great numbers. Some 30,000 homes were without power in Albany, Schenectady, Troy area alone with states of emergency declared by authorities in these cities as well as in Saratoga Springs, Glens Falls, and a number of smaller communities. Highways and streets closed throughout area because of fallen wires, trees, and limbs as surface travel became extremely hazardous; air travel was halted until end of storm. Widespread damage to buildings, cars, etc., from broken limbs and trees. Nearly two weeks required to completely restore power; schools remained closed through most of week following storm. Dairy farms, many commercial and industrial establishments suffered damage to goods and hardship due to power failures.

Thousands of people forced to shelter for several days in schools, armories and churches. Youth killed at Hudson Falls from stepping on live wire. Thawing of heavy ice on wires on Dec. 11 caused additional power failures as wires snapped from sudden release of weight. Same storm also wrought important but much less damage to trees and power lines in a belt south of Lake Ontario and extending from the Mohawk Valley and Otsego County westward to include Erie and Wyoming Counties. Areas thus affected by freezing rain included Buffalo, Rochester, Canandaigua, Oswego, Syracuse, Utica, and sections of southern Lewis and Jefferson Counties. Effects of storm relatively light and minor in sections of Catskills and southern half of Hudson Valley.

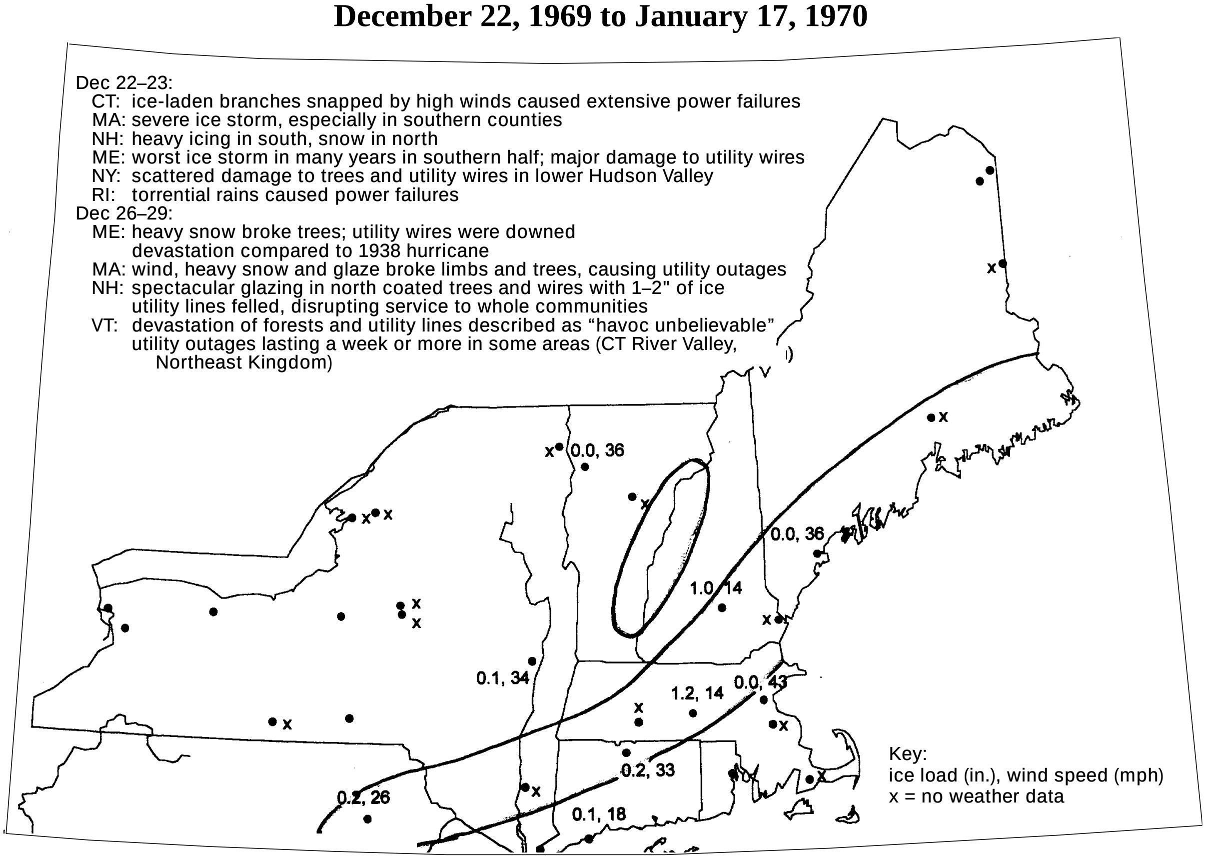
12/11/64
MAINE State [ME01>14] IC2 (Glaze)—Freezing rain glazed many sections of Maine and produced hazardous streets and walks. Many minor accidents followed.

12/11/64
MASSACHUSETTS Western portion [MA05,06] IC2 (Glaze)—Freezing rain glazed roads and walks in some communities.

12/11/64
NEW HAMPSHIRE State [NH01>07] IC2 (Glaze)—Freezing rain produced glazing in many communities.

12/11/64
VERMONT State [VT01>05] IC2 (Glaze)—Freezing rain produced glazing in many communities.

December 22, 1969 to January 17, 1970



Storm Data

The ice storm of December 26–27 in the Connecticut River Valley is described in Ackley and Itagaki (1970).

12/22/69
CONNECTICUT
East Windsor, Enfield, Suffield; Hartford Co. and Winsted, Torrington; Litchfield Co. [CT01,02]
Glaze, wind
Ice-laden branches, snapped by high winds, caused extensive power failures. Glazed roadways were responsible for several skidding accidents.

12/22–23/69
MAINE
Southern half [ME04,07,08,10>14]
Glaze
The worst ice storm in many years. Major damage to utility wires. Many accidents occurred on the icy roads. Thousands of ice-laden trees and limbs toppled, taking utility wires with them. Falling trees also damaged homes and blocked highways. Downed live wires added to the danger. The freezing rain changed to rain before ending. Underpasses and other low spots flooded and many cars stalled.

12/22/69
MASSACHUSETTS
Central and western [MA04>07]
Glaze and snow
A severe ice storm, especially in southern counties. Trees and limbs breaking under the weight of ice downed utility wires. In Clinton some cars were damaged by falling trees. Power outages were widespread. Many Christmas decorations were victims of the ice. In the north and northwest precipitation was mostly snow, accumulation to 16 in. at North Adams.

12/22/69
NEW HAMPSHIRE
State [NH01>07]
Snow, glaze
Storm yielded more than a foot of snow in northern sections and heavy icing in the south. Widespread power failures, traffic jams, and many skidding accidents occurred.

12/22/69
NEW YORK
Hudson and Mohawk Valleys and Eastern Plateau [NY13,14]
Snow, freezing rain
First major storm of the winter in eastern sections produced heavy snowfall between the Susquehanna River watershed and the Hudson River Valley. Snowfall totals of 10- to 14 in. in Hudson Valley from Poughkeepsie to Glens Falls and in eastern Mohawk Valley produced hazardous highways, snarled city traffic, and many skidding accidents. Several incidents of large freight

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and gasoline tricks overturned or jackknifed on highways. Eastern Plateau areas as far west as Bromme and Chenango Counties blanketed with 8- to 12 in. of snow with up to 16 in. in higher elevations of Catskills. Winds were light to moderate and problems of drifting and blowing snow were minor. One dairy barn collapsed from weight of snow in Sullivan County. Freezing rain occurred in the lower Hudson Valley from Orange to Putnam and southern Dutchess Counties, where scattered, but locally moderate, damage resulted to trees, limbs, and utility wires. Power failures lasted up to 48 hours after storm. Rain totaling 1–1.5 in. fell in New York City and coastal counties. Storm brought 4–8 in. of snow to northeastern NY and eastern Finger Lakes and light amounts to areas near Great Lakes.

12/22/69
RHODE ISLAND
Statewide [RI01,02]
Rain, glaze
Torrential rains of 1–2.5 in. and wind were responsible for power failures in Providence, South Providence, and Warwick and for extensive flooding in Pawtucket, Warwick, Cranston, East Greenwich, and Middletown. Glaze, the result of a rapid temperature drop, caused extremely hazardous driving conditions. At Tiverton, a gust of wind flipped a compact vehicle onto its back and a passenger was injured.

12/25–28/69
MASSACHUSETTS
State [MA01>09]
Snow, rain, glaze, wind
A devastating “northeaster.” Snow began late on Christmas Day, accumulation mostly 1–2 ft over state. Some higher totals in Berkshires, locally to 3 ft, where storm continued mostly as snow. Elsewhere storm changed to freezing rain, sleet, and rain during the day of the 26th. On Cape Cod and the immediate coast, snowfall ranged mostly from only a trace to 6 in. before changing to rain. Weight of snow and rain collapsed roofs. New record 24-hour precipitation totals for Dec. were received as over 4 in. fell in parts of eastern Mass. Total storm precipitation ranged from about 2 in. in much of the western portion to 3–5 in. in the east, with some locally over 6 in.. The snow hampered drainage, causing severe local flooding from the rain. Many roads flooded as did cellars. Some homes had to be evacuated with water 4 ft or higher in yards. In Boston the Christian Science Monitor publishing plant was flooded. A dam was partially washed away in West Bridgewater. The rain-soaked snow was especially hard to plow or shovel, and all forms of transportation were slowed or halted. Heavy snow and glaze on trees broke limbs or caused whole trees to topple in the wind, causing utility outages. Winds were strongest in the Cape Cod area, where gusts of nearly 100 mph were reported. Two deaths in the greater Boston area were attributed to exhaustion by the storm.

12/26–27/69
CONNECTICUT
Statewide [CT01>06]
Snow, glaze, rain, wind, thunderstorms

After a lull of only 24 hours, another and more intense coastal storm began affecting CT on the 25th but major results were postponed until the 26–27th before the storm moved off on the 28th. The storm began as snow but turned to freezing rain and sleet over the interior and rain along the coast on the morning of the 26th after snowfalls of 6–17 in. Storm precipitation totals reached 1–2 in. in the west and 2–4 in. in the east. Flood tides, accompanying the storm, swamped low areas along Long Island Sound and locally serious flooding occurred in scattered places in the interior. The storm brought all business, commercial, and educational activities to a halt, was responsible for exceedingly hazardous roadways, and knocked out power and communication lines. Several thunderstorms occurred on the 26th and dangerous sheets of ice caused many accidents as late as the 26th.

12/26–28/69
MAINE
Central and southern [ME03,04,06>14]
Snow, glaze, rain, lightning, wind
A devastating "northeaster." Heavy snow totaled mostly 6–18 in. on the 26th before changing to sleet, freezing rain, and rain. Trees and limbs broke by the thousands, with devastation compared to that of the 1938 hurricane. Utility wires were downed, disrupting service to many communities, some for the second time the same week. Heavy rain further weighted the snow, causing many roofs to collapse or leak. Some buildings collapsed. These included some barns in Franklin Co. in which several cows were killed. The combination of snow and rain caused severe flooding. The town of Phillips was completely cut off, while all major routes into Farmington were also closed by water. At Farmington, the storm was said to be the worst in memory of even the oldest citizens. Cellar flooding was common, putting more furnaces out of service. Storm precipitation totaled mostly 2.5 in. at Farmington, and 6 in. as far north as Jackman. Lightning on the 26th struck a home in Wiscasset. Death of a man in Rumford was partially blamed on the storm, which prevented help from reaching his burning house. Wind also contributed to the devastation. A plate-glass window was broken at Rockland, where gusts to 80 mph were reported. Piers, boats and coastal installations were battered by wind and high surf. Beach erosion was extensive in the Biddeford–Saco area. Damages in Waldo Co. alone were estimated at over a half-million dollars. Much milk had to be dumped by dairymen due to loss of power or lack of transportation. One death in the Portland area from exhaustion by the storm.

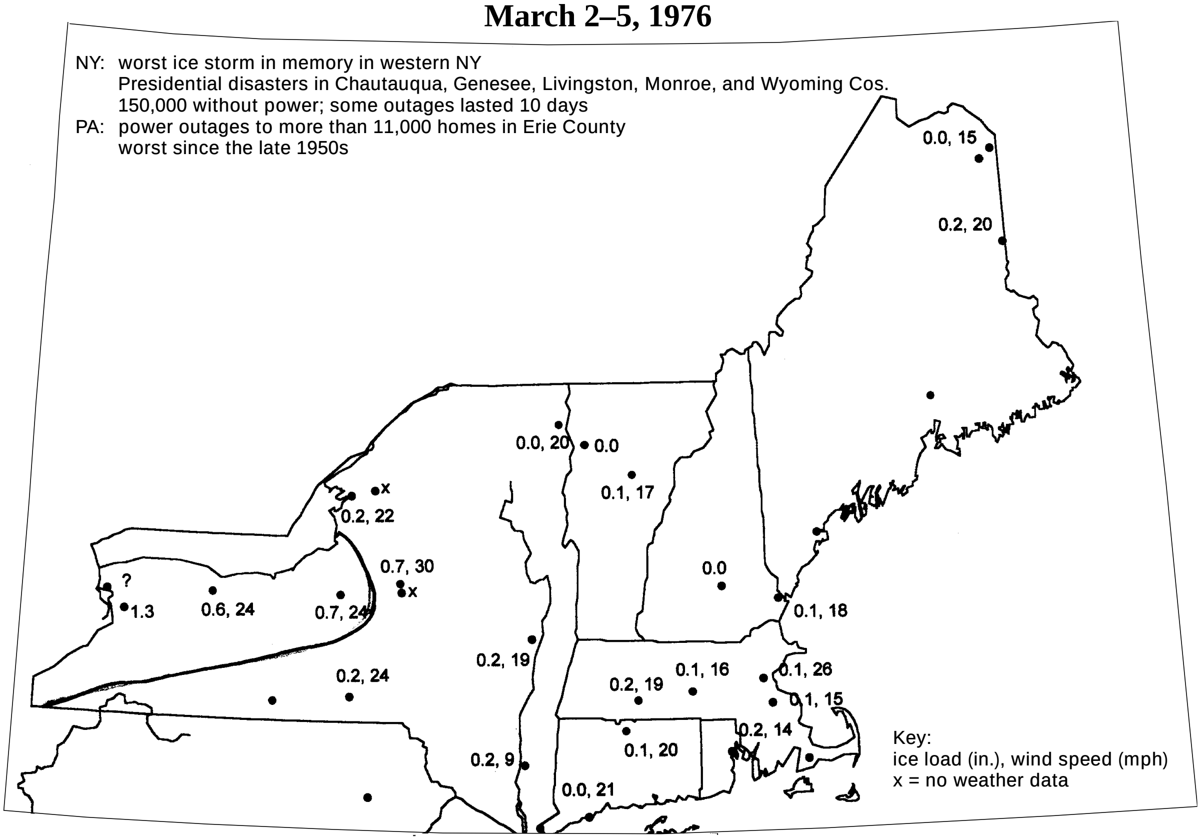
12/26–28/69
NEW HAMPSHIRE
State [NH01>07]
Snow, rain, glaze, wind, lightning
A devastating northeaster. Snow accumulated mostly 10–20 in. deep on 26th before it changed to sleet, freezing rain, and rain. Spectacular glazing in north coating twigs and wires with 1–2 in. of ice. Trees and limbs broke under the weight, in some areas with damage comparable to that of the 1938 hurricane. Utility lines were felled, disrupting service to whole communities, some for the second time in the same week. Rain further weighted the snow, causing many roofs to collapse or leak. Some barns and other buildings collapsed. A church and gas station were affected in Dover. Especially in the southern portion, heavy rain caused flooding of roads and cellars, in

part due to poor drainage on account of the snow. Lightning accompanied the storm on the 26th in some areas. One death from exhaustion occurred in the Concord area. Wind added to the devastation of trees and in Hampton Beach windows were blown out. Considerable damage to shoreline and coastal installations from high wind and surf, with flooding of some coastal roads. Much milk had to be dumped by dairymen in state due to lack of electricity or transportation. The storm precipitation totaled mostly 3–5 in. but some heavier in the White Mountains area.

12/26–27/69
RHODE ISLAND
Statewide [RI01,02]
Snow, freezing rain, rain
Severe coastal storm began on evening of 25th with snow accumulations of 6–11 in. on mainland by morning of 26th. Precipitation then changed to freezing rain and rain with storm totals reaching 3–4 in. before ending as freezing rain and snow on the 26th. Massive traffic jams occurred on the 26th and many skidding accidents occurred especially from Providence to Kingstown and to Newport. A late afternoon fog on the 26th made driving especially hazardous in S. Kingstown and Narragansett. Extensive flooding occurred in Providence, Cranston, W. Warwick, Newport, Rumford, and N. Kingstown. Some communications were lost as water seeped into power lines. Storm halted all activity on land and in the air on the 26th and hampered business and transport on the 27th.

12/26–28/69
VERMONT
State [VT01>05]
Snow, glaze, wind
A devastating "northeaster." Snowfall totaled mostly 1.5–3 ft but up to a new Vermont storm record 45 in. at Waitsfield. This closely followed a major snowstorm earlier the same week. The state was officially declared a disaster area by the governor. Drifts commonly mounted up to 6 ft and in some local areas up to 30 ft, closing roads and halting virtually all transportation except by snowmobile. Storm changed to freezing rain and sleet along the CT River and in the Northeast Kingdom area. Ice built up to over 2 in. in many areas with some local reports of 3–6 in. on wires and twigs. Devastation of forests and utility lines was described as "havoc unbelievable." Weight of snow and ice collapsed many roofs and buildings, both rural and urban. Cows were killed in two of the several barns collapsed. A poultry house collapse killed most of 10,000 chickens. A number of commercial and factory roofs collapsed in the Middlebury and Rutland areas. One death was attributed to the storm in the Saxtons River area. Dairymen were especially hard hit by loss of power for milking and had to dump thousands of gallons of milk due to lack of storage or transportation. Utility outages were prolonged in many areas, up to a week or more.

March 2–5, 1976

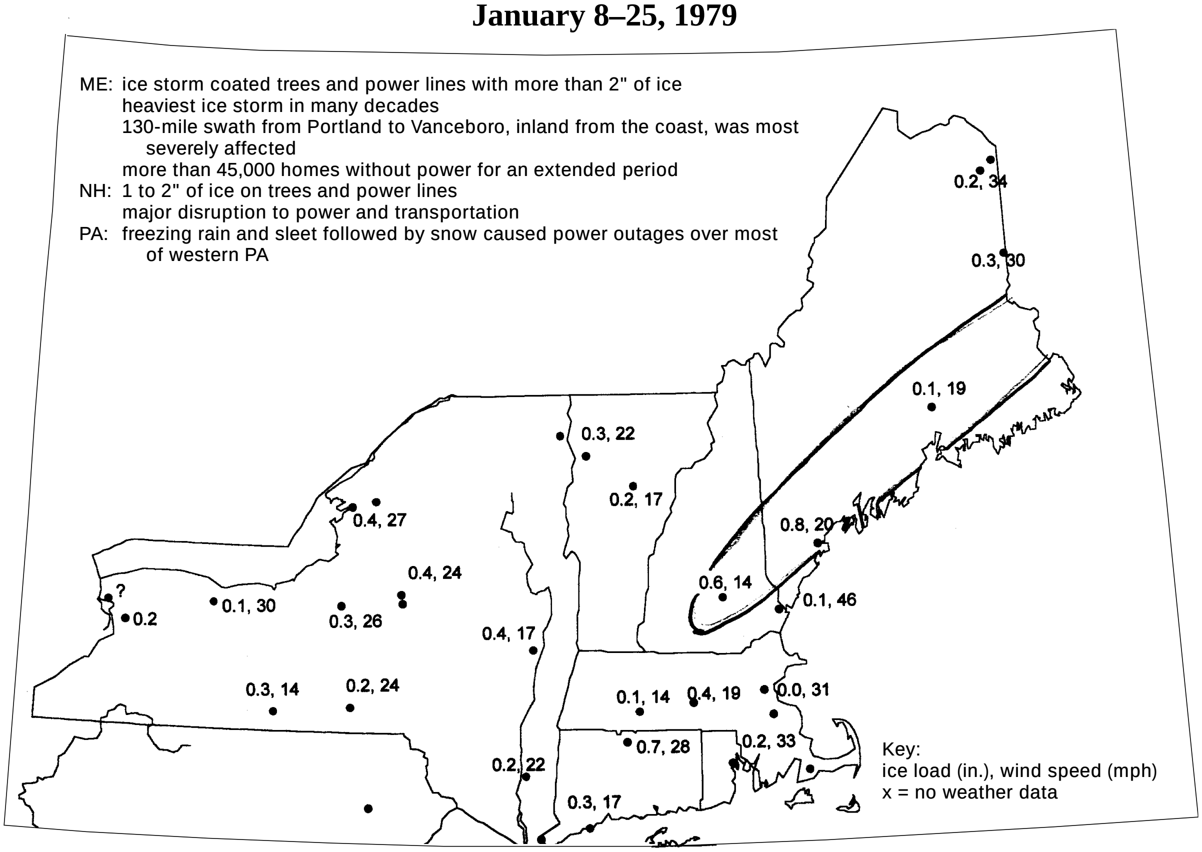


Storm Data
3/2–3/76
NEW YORK
Western Finger Lakes Counties and extreme Western NY
[1/3, 5, 21, 22]
(Ice Storm)
IC5
March 1976
The worst ice storm in memory paralyzed much of Western NY. Freezing rain began early morning of the 2nd and ended about noon on the 3rd. One report said ice was 4 in. thick. The following counties were declared major disaster areas by President Ford: Chautauqua, Genesee, Livingston, Monroe, and Wyoming. One person was killed and one seriously injured in the Town of Evans when their car skidded on ice. One third of trees in Buffalo alone were badly damaged by weight of ice. Massive damage to electrical power lines caused major blackouts. Some blackouts

lasted 10 days or so. Many roads were blocked by fallen trees and wires. In Buffalo 200 streets were blocked, some for several days. A major problem was flooding of basements when electrical sump pumps became inoperative. This storm was probably the most costly ever and affected the most people. Damages were estimated as follows: Erie County $75 million, Chautauqua $8 million, Livingston $1 million, Genesee $1 million, Wyoming $750,000, and Monroe $450,000. From 110,000 to 150,000 homes were without power for heat and light. Water utilities lost power and at least 10,000 homes were without water.

3/2–3/76
PENNSYLVANIA—Western
Erie County
[1]
(Ice Storm)
IC3
March 1976
Ice coated everything; trees and power lines down, causing power outages in more than 11,000 homes. Houses and cars hit by falling trees. The number and scattered locations of power outages in Erie area probably has not been equaled since the late 1950s, according to local authorities. Bridges over West Fork branch of French Creek washed out, plunging a car into the creek. Driver not seriously injured.

January 8–25, 1979



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1/7–8/79
PENNSYLVANIA
W Cos.
PA01>03,15
IC3
Ice, heavy snow
Freezing rain and sleet followed by 2–4 in. of snow caused hazardous driving conditions, school closings, and power outages over most of W PA. In some sections there was between 6–10 in. of snow. There was one fatality. A man driver lost control of his car and skidded sideways on an ice-covered road and into a tree. Two passengers were injured.

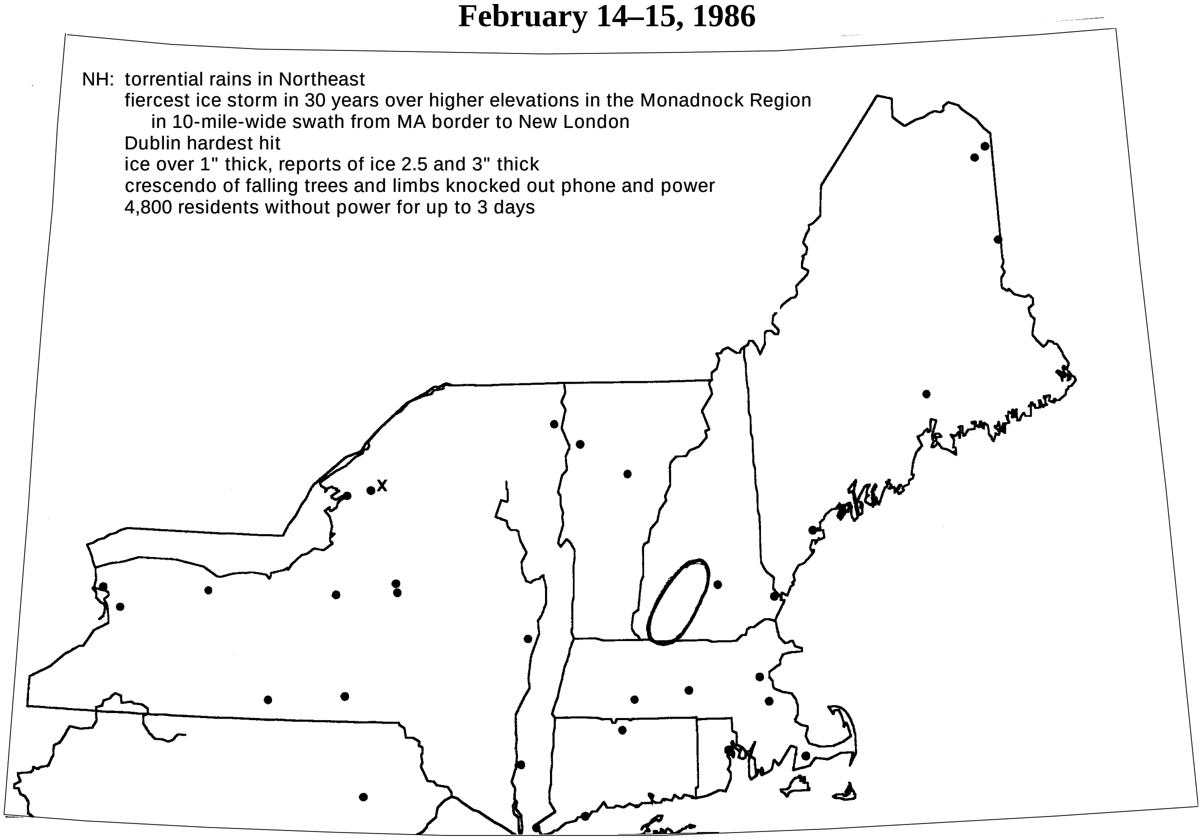
1/7–8/79
MAINE
Southern
ME4,8,11,14
IC3
Ice storm
An ice storm, the heaviest in many decades, glazed roadways and coated trees and powerlines with more than 2 in. of ice. A 130-mile swath from Portland to Vanceboro, inland from the coast, was most severely affected. More than 45,000 homes were without power for an extended period. Falling trees and branches snapped power lines. Countless storm-related traffic accidents. Schools and businesses closed. Orchardist reported moderate damage to fruit trees.

1/7–8/79
NEW HAMPSHIRE
Statewide
NH01>07
IC3
Freezing rain
Snow, sleet, and freezing rain accumulated 1–2 in. of ice on trees and power lines. Major disruption of power and transportation. Many businesses and schools closed. Slush and snow plugged catch basins with widespread street and highway flooding. Ice-covered roads resulted in many storm-related accidents.

1/20–21/79
PENNSYLVANIA
Eastern
PA07>12,16
IC2
Ice storm, rain, flooding
Sleet and freezing rain on the 20th caused very hazardous driving conditions and downed tree limbs and power lines. Many automobile accidents resulted and 10,000 or more customers had power outages. The precipitation changed to all rain and continued most of the 21st with precipi-

tation amounts of 1–3 in. The melting ice and sleet plus the rain caused widespread roadways, drainage, and stream flooding. Many basements were flooded and about 40 people had to be evacuated from their homes.

February 14–15, 1986



Storm Data
2/14–15/86
NEW HAMPSHIRE
Monadnock Region; Cheshire, Sullivan, and W. Halves of Hillsborough and Merrimack Counties.
NH03>06 (Ice Storm)
A stationary front offshore ran from the New Jersey coast to south of Nova Scotia, Friday morning. A low-pressure area formed on the front south of New England late Friday, moved across Cape Cod Saturday morning, and was east of Nova Scotia Saturday night. This system brought torrential rains to the northeast. However, with temperatures hovering around the freezing mark over the higher elevations of the Monadnock Region, it produced the fiercest ice storm in 30 years. A swath about 10 miles wide and 60 miles long stretched from the Massachusetts border to New London (Merrimack County) where authorities said the ice was over one inch thick with several reports of 2 1/2 to 3 inches of ice accretion. The "crescendo of falling trees and tree limbs," Friday night and Saturday, knocked out telephone and power lines and blocked roads. Dublin (Cheshire County) was the hardest hit area, where the weight of the ice cracked 18 utility poles, pulled down a one-mile stretch of power lines, and snapped numerous trees that were one foot in diameter. A house fire in Dublin was caused by a power surge. Firemen took 20 minutes

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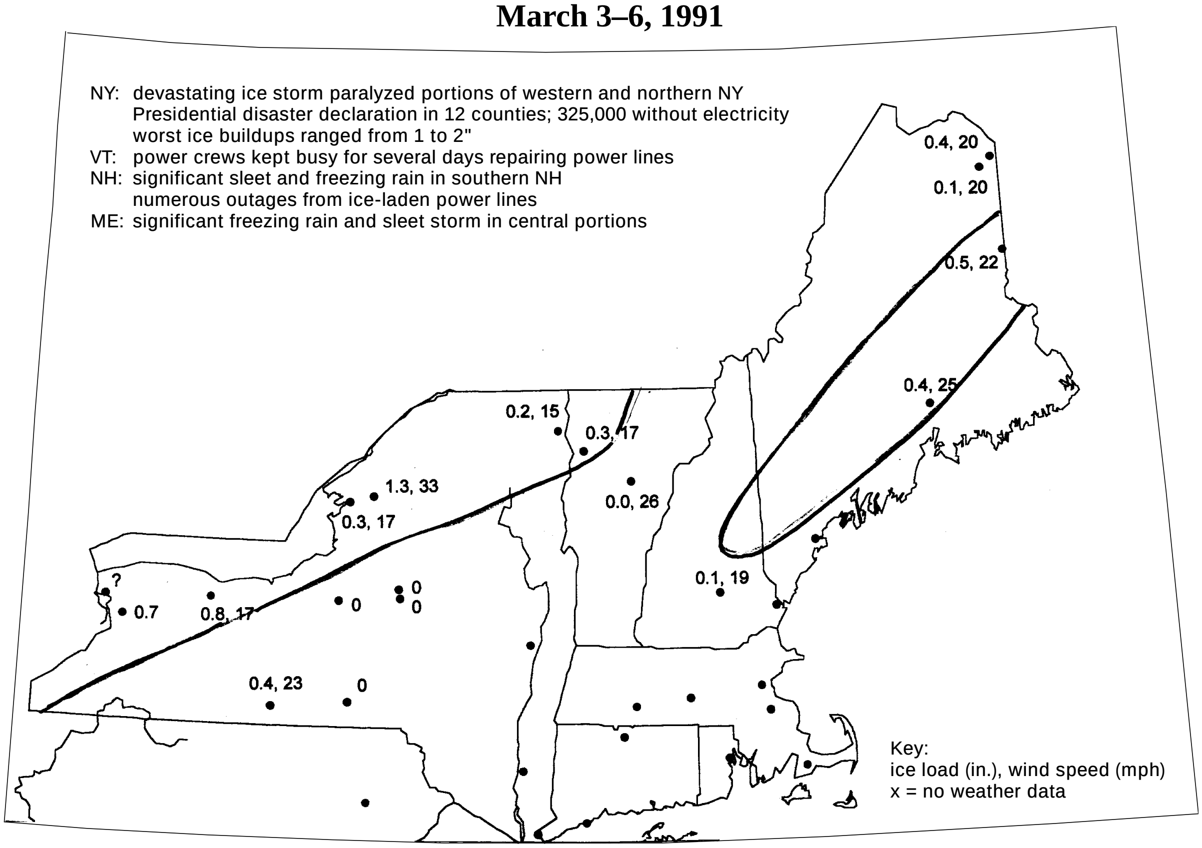
to cut their way through the tree-blocked roads to reach the blaze. Once there, they not only fought the fire, but dodged falling trees, tree limbs, and huge ice chunks. No one was injured, nor was any of the fire trucks damaged. In the Monadnock area, some 4800 residents were without power and about 200 homes lost telephone service for up to 3 days. Outside this swath, ice problems were hardly noticeable. The rains produced minor flooding of roads in Winchester, Hinsdale, and Ashuelot (Cheshire County).

March 3–6, 1991



Storm Data
3/3–4/91
NHZ004-006-007 Southwestern New Hampshire NHZ001-002 Northern New Hampshire (Freezing Rain)—On March 3rd, a cold front moved east from the Great Lakes area through southeastern Canada. Meanwhile, a low-pressure system over Georgia was moving northeast. The Georgia low intensified and moved up the coast as cold air continued to flow into northern New England from the Arctic high. By the time the precipitation arrived in northern New England, enough cold air was present in the lower levels of the atmosphere to produce a significant freezing rain and sleet event in southern New Hampshire, and heavy snow in the north. High winds caused trees and limbs to go down on power lines, disrupting power from 90 minutes to 2 hours for 150 to 220 customers in the Rochester and Milton areas. There were numerous power outages elsewhere across the state due to the weight of ice-laden power lines. The freezing rain also caused numerous schools and businesses to shut down for the day.

3/3–4/91

NYZ007-008-011-018 St. Lawrence Valley, Eastern Adirondacks, Champlain Valley, Western Adirondacks (Freezing Rain)—St. Lawrence County was part of the central New York area that was hard hit by a major ice storm. More than 9000 homes were without power, 60 automobile accidents were reported, mail delivery halted, all schools and colleges were closed for several days, and businesses were shut down. Elsewhere in the Adirondacks, the ice presented fewer and more scattered problems. The storm built in intensity through Sunday night. By Monday morning, more than 2 in. of ice had accumulated in some low-lying areas. In higher elevations the freezing rain was reported to have changed to snow before ending on Monday.

3/3–4/91

NYZ002 Monroe, Ontario, Wayne, Yates, and Livingston Counties NYZ004 Lewis, Oswego, and Jefferson Counties NYZ003 Steuben County NYZ022 Allegheny and Cattaraugus Counties NYZ021 Orleans County NYZ001 Wyoming and Genesee Counties (Ice Storm, Heavy Snow, Ice)—A devastating ice storm paralyzed a large section of western and portions of northern New York. The freezing rain began during the late afternoon of Sunday the 3rd, continuing through the morning of the 4th. The ice coated trees and power lines and sent them crashing to the ground along with utility poles and transformers. There were also numerous reports of structural damage from the weight of the ice. Ice buildups ranged from 1 to 2 in. over the hardest-hit areas. Over the western fringes of the storm area, the coating of ice was followed by 4 to 6 in. of heavy, wet snow. At its peak, nearly 325,000 customers were without electricity. Virtually all schools and businesses were shut down Monday and Tuesday (March 4th and 5th) in the affected areas. In the cities of Rochester and Watertown, schools were closed for the entire week. High water in flooded basements was commonplace when sump pumps were unable to work due to power failures. Governor Mario Cuomo declared 18 counties state disaster areas. State agencies were authorized to provide manpower and equipment in helping residents affected by the storm. Utility crews were brought in from Ohio, Pennsylvania, and Canada to aid in the restoration of power, which was not accomplished until March 16th. President Bush signed an order declaring 12 counties federal disaster areas. It was the most costly natural disaster in the history of New York State.

3/3/91

Vermont Statewide (Freezing Rain)—Freezing and brief periods of sleet, snow, fog, and rain made a mess of Vermont celebration of 200 years of Statehood. Power crews across the state were kept busy for several days repairing power lines. A 30-month-old girl and her 5-year-old sister were rescued from near drowning after a car accident which sent their vehicle into the river. Police blamed the accident on icy roads. Portions of Interstate 89 were closed to traffic.

3/4/91

Maine mez00-002-003-005-006-007-009-010-012 All But Coastal Maine (Freezing Rain)—On the 3rd of March, a cold front moved south through New England. A large Arctic high-pressure system moved east from the Great Lakes area through southeastern Canada. Meanwhile, a low-pressure system over Georgia was moving northeast. The Georgia low intensified and moved up the coast as cold air continued to flow into northern New England from the circulation around the Arctic high. By the time the precipitation arrived in northern New England, enough cold air

was present in the lower levels of the atmosphere to produce a significant freezing-rain and sleet event in central portions of the state, and heavy snow in the north. High winds toppled trees and limbs onto power lines in southwestern Maine causing power outages in York, Kittery, and Eliot Counties affecting some 5000 customers. A downed tree on Route 236 in Berwick caused traffic problems. An unusually high tide in conjunction with this storm knocked a house off its pilings and onto the beach at 7 Eastern Avenue in the Camp Ellis section of Saco. The house was valued at $145,500 per tax records. The extent of this damage was not reported. Moreover, this late winter storm forced the state government to advise 12,000 state employees to stay at home until noon because of ice on the roads. Therefore, for half of a day, the state government was shut down and some state courts were disrupted. Also, numerous schools were closed due to dangerous road conditions. Some of the schools closed on the 5th as well—school official couldn't recall any school closures for two days in a row because of a winter storm since the big blizzard of 1969.

3/4/91
PAZ001 Erie, Lakeshore PAZ002 Northwestern Portion PAZ003 Western Portion (Ice Storm)—Ice-coated power lines and branches with ice 1 in. thick caused a total of 40,000 people to lose power in northwestern Pennsylvania.